BTC Method *for* Evaluation of Remaining Strength and Service Life of Bridge Cables

NYSDOT REPORT C-07-11

FINAL REPORT

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New York State Department of Transportation

New York State Bridge Authority

In cooperation with the

U.S. Department of Transportation

Federal Highway Administration

BRIDGE TECHNOLOGY CONSULTING

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DISCLAIMER

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This report presents the BTC method; a comprehensive state-of-the-art methodology for evaluation of remaining strength and residual life of bridge cables. The BTC method is a probability-based, proprietary, patented, and peer-reviewed methodology, which applies to parallel and helical; either zinc-coated or bright wire of suspension and cable-stayed bridge cables. The BTC method includes random sampling without regard to wire appearance, mechanical testing of wires, determining the probability of broken and cracked wires, evaluating ultimate strength of cracked wires employing fracture mechanics principles and utilizing the above data to assess remaining strength in each investigated length of the cable. The probabilistic-based BTC method forecasts remaining service life of the cable by determining the rate of growth in broken and cracked wires proportions detected over a time frame, measuring the rate of change in effective fracture toughness over same time frame, and applying the rates of change to a strength degradation prediction model. The BTC method provides sensitivity analysis to identify the key inputs, which influence the estimated cable strength and assist decision-making process. The report describes the application of BTC method at Mid-Hudson Bridge in New York, conducted by Bridge Technology Consulting (BTC), under a joint contract with New York State Department of Transportation (NYSDOT) and New York State Bridge Authority (NYSBA). This project is funded in part with funds from the Federal Highway Administration (FHWA). The BTC method has been peer-reviewed by MTA Bridges & Tunnels, NYSDOT and NYSBA. To date, the BTC method has been applied to evaluate cable strength at the Bronx-Whitestone Bridge and Mid-Hudson Bridge, in the state of New York, USA.</td></tr>
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TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report presents the BTC method; a comprehensive *state-of-the-art* methodology for evaluation of remaining strength and service life of bridge cables. The BTC method is a probability-based, proprietary, patented, and peer-reviewed methodology, which applies to parallel and helical; either zinc-coated or bright wire of suspension and cable-stayed bridge cables. The BTC method includes random sampling without regard to wire appearance thus eliminating bias associated with visual evaluation of wire condition, mechanical testing of wires, determining the probability of broken and cracked wires, evaluating ultimate strength of cracked wires employing fracture mechanics principles and utilizing the above data to assess remaining strength in each investigated length of the cable. The probabilistic-based BTC method forecasts remaining service life of the cable by determining the rate of growth in broken and cracked wires proportions detected over a time frame, measuring the rate of change in effective fracture toughness over same time frame, and applying the rates of change to a strength degradation prediction model. The BTC method provides sensitivity analysis to identify the key inputs, which influence the estimated cable strength. The sensitivity analysis assists the bridge owner in decision-making strategies related to future inspections and condition evaluations of bridge cables. The high level of confidence in the results of BTC method translates into a paradigm shift in evaluation of remaining strength and residual life of bridge cables. This provides optimization of financial resources and significant savings in the cost of inspection and condition evaluation of bridge cables.

New York State Department of Transportation (NYSDOT) and New York State Bridge Authority (NYSBA) jointly retained Bridge Technology Consulting (BTC) to apply the BTC method to evaluate remaining strength and residual life of main suspension cables at the Mid-Hudson Bridge in Highland, New York, USA. This project is funded in part with funds from the Federal Highway Administration (FHWA). The BTC method has been peer-reviewed by MTA Bridges & Tunnels, NYSDOT and NYSBA. To date, the BTC method has been applied to evaluate remaining strength and residual service life of main suspension cables at the Bronx-Whitestone Bridge and Mid-Hudson Bridge, in the state of New York, USA. This NYSDOT Report C-07-11 describes main suspension cable strength evaluation, utilizing the BTC method, at the Mid-Hudson Bridge.

Under this contract a total of eight (8) panels were unwrapped, wedged and inspected. Random samples were extracted from each of the eight (8) panels in accordance with the BTC method random sampling plan. Wire samples were then sent for testing mechanical properties. Test data results were used in the probabilistic-based BTC method to evaluate cable strength and corresponding factors of safety in each of the eight (8) investigated panels. The residual service life of the cable was assessed at the controlling panel.

During field inspection, counts of broken wires were recorded, and wire samples were extracted for testing from each of the eight (8) investigated panels. Proportion of broken wires, in each of these panels, was treated in the analysis as a probabilistic quantity. There are various sources of error in the process of cable strength evaluation. One of the main sources of error is due to the unfeasibility of sampling and testing each wire in the cable, therefore only a sample of wires were taken to test for mechanical properties. The error associated with this process is called the

sampling error. To minimize the sampling error, previous test data was utilized to establish a correlation between sample size and error in the estimated cable strength. In this investigation, we aimed at limiting the sampling error in the estimated cable strength to 5%. This resulted in a sample size of 15 wires in each of the eight (8) investigated panels. The sample size of 15 wires was randomly selected per BTC sampling plan in each investigated panel. The inspectors had no role in selecting the sampled wires thus eliminating bias in the sampling procedures.

In this cable investigation we undertook particular effort to better understand the extent and effect of cracking in wires on the estimated cable strength. Previous studies have used very limited data and did not include fracture-based analysis of cracked wires in the assessment of cable strength. Under this project, the entire set of fracture surfaces of wires tested in the laboratory was examined under stereomicroscope for presence of preexisting cracks. In each of the investigated panels, stereomicroscope examination determined the cracked wire proportion. This was in turn treated as an input probabilistic quantity in the BTC method. Fracture mechanics principles were employed to assess the fracture capacity of cracked wires based on measured crack depth and effective fracture toughness evaluation of degraded wires. The fracture toughness of bridge wire was determined by BTC at the Mid-Hudson Bridge under a previous contract.

The results obtained from laboratory testing were used to estimate the strength of main cables in the eight investigated panels. The controlling panel under this investigation, PP 133N-134N, PSS, along the north cable, stands out as the most degraded panel among the eight investigated panels. It contains the highest proportions of both; cracked and interior broken wires. The expected safety factor, based on expected value of cable strength, at the controlling panel, PP 133N-134N, PSS, along north cable is 2.75. The cable strength and corresponding safety factor have declined, up to 25%, at the controlling panel, PP 133-134, PSS, north cable as follows:

Safety Factor at PP 133-134, PSS, North Cable

Original Design (FS) - 1930	3.68
Current Condition (FS) - 2009	2.75

According to analysis of strength degradation, at the controlling panel, PP 133-134, PSS, north cable, it is the BTC method forecast that the factor of safety will reach the critical value of 2.0 in year 2041. This estimates that the remaining service life of the cable is 30 years. The forecast of cable service life in the BTC method incorporates the effect of both; broken and cracked wires in adjacent panels, which is called thereafter, the effect of adjacent panels.

Sensitivity analysis was performed to demonstrate how the key inputs affect the cable strength and assist the bridge owner in decision-making process regarding future cable inspection and evaluation projects.

Recommendations

Based on the analysis of data and the resulting cable strengths and factors of safety, the following summarizes our recommendations:

- The effect of adjacent panels has a significant impact on the estimated cable strength. Therefore it is our recommendation to wedge, inspect, sample and test wires from at least one adjacent panel at each end of the controlling panel, PP 133-134, PSS, along north cable, during next cable investigation.
- Continue the current program of in-depth cable investigation on a 5-year cycle. During next cable opening in 2014, we recommend at minimum four (4) panel openings on south cable and six (6) panel openings on north cable; three of which are PP 133-134, PSS, along with its two adjacent panels.
- It is shown that there is little correlation, if any, between degradation of cable strength and visual-based evaluation of corrosion on wire surface, as defined by NCHRP Report 534 Guidelines.
- It is demonstrated in the sensitivity analysis that cracking in the wires has primarily driven the strength degradation. Therefore thorough fractographic evaluation of test samples and fracture-based analysis of cracked wires are essential in upcoming cable investigations.
- Random sampling of wires, without regard to wire appearance, eliminates bias in selecting wires for testing. Therefore BTC recommends random sampling procedures in future investigations.
- It is our recommendation to consider the required lead-time to commence cable augmentation, so the mitigating measures can be in place ahead of 2041.

ACKNOWLEDGEMENTS

Bridge Technology Consulting (BTC), under NYSDOT Project C-07-11 *BTC Method for Evaluation of Remaining Strength and Service Life of Bridge Cables*, produced this report. The Principal Investigator (PI) is Dr. Khaled M. Mahmoud, P.E.

The Project Manager was Dr. Sreenivas Alampalli, P.E. from New York State Department of Transportation (NYSDOT), and Technical Working Group (TWG) members were George Christian, P.E. from NYSDOT, William J. Moreau, P.E. from New York State Bridge Authority (NYSBA) and Dr. Deniz Sandhu from NYSDOT. The author acknowledges the support provided by NYSDOT and NYSBA, and members of the Project Technical Working Group, who met periodically with BTC, provided comments and reviewed project task submissions, and draft reports all along toward the successful completion of this report.

The author is grateful to the peer reviewers of the BTC method for cable strength evaluation; Professor John W. Fisher of Lehigh University, Professor Theodore V. Galambos of the University of Minnesota, Professor Alan W. Pense of Lehigh University, and Professor Habib Tabatabai of the University of Wisconsin Milwaukee, for providing insightful comments and useful discussions.

INTRODUCTION

This project is sponsored by New York State Department of Transportation (NYSDOT), New York State Bridge Authority (NYSBA) and is funded in part with funds from the Federal Highway Administration (FHWA).The Principal Investigator (PI), from Bridge Technology Consulting (BTC), is Khaled Mahmoud, Ph.D., P.E. The NYSBA and the NYSDOT were responsible for review and approval of all task submissions made by BTC.

Given the importance of cable-supported bridges, random sampling and reliability-based analytical techniques are required for the assessment of remaining strength and residual life of the cable. State-of-the-art assessment techniques employ reliability criteria (similar to LRFD criteria), in which strength, strain and loads are known as probabilistic quantities. If an evaluation is conducted using these criteria, the results can be used to establish the frequency of future cable inspection and evaluations. Once probability distributions for wire mechanical properties, such as strength and strain, and probability of broken and cracked wires are established, it's possible to develop a cable failure mechanism and assess the serviceability of the cable. Use of probabilistic analysis in this approach is similar to the LRFD probabilistic analysis employed in the current AASHTO standards.

BTC Method for Cable Strength Evaluation

The analysis of cable strength in this report is based on the BTC method; a comprehensive *state-of-the-art*, probability-based, proprietary, patented, and peer-reviewed methodology for the evaluation of remaining strength and residual life of bridge cables. The BTC Method applies to parallel and helical wires; either zinc-coated or bright wire of suspension and cable-stayed bridge cables; includes random sampling without regard to wire appearance; mechanical testing of wire samples; probability of broken and cracked wires; evaluating ultimate strength of cracked wires employing fracture mechanics principles and utilizing the above data to assess remaining strength of the cable in each panel. The BTC method forecasts remaining service life of the cable, under the combined effect of loading and environment, by determining the rate of growth in broken and cracked wires proportions detected over a time frame, measuring the rate of change in effective fracture toughness over same time frame, and applying the rates of change to a strength degradation prediction model. The BTC method performs sensitivity analysis to identify the key inputs which influence the estimated cable strength and assist the decision-making process. This provides bridge owners with the information necessary for planning and budgeting future cable inspections and strength evaluations. With random sampling, fracture mechanics principles, and probabilistic-based analysis, the BTC method provides higher level of confidence in the estimated strength and assessed remaining life of the bridge cable.

The formulation and derivation of the BTC method have been developed prior to this project.

The BTC method includes the following:

- Random sampling for wires in each of the specified cable openings.
- Fracture testing and fracture mechanics analyses to evaluate current and future estimate of cable strength.

- Incorporates effect of ultimate strength and ultimate strain of tested wires.
- Reduces the uncertainties associated with proportions of cracked wires, and subjectivity inherited in visual-based assessment.
- Assesses and classifies wire degradation based on actual measured test data.
- Employs a comprehensive statistical approach to the analysis that produces panel-by-panel cable strength.
- Provides sensitivity analysis to assist bridge owner in decision-making.
- Forecasts future cable strengths; providing invaluable information regarding cable strength degradation rate.

The BTC method has been peer-reviewed by MTA Bridges & Tunnels (TBTA), New York State Department of Transportation and New York State Bridge Authority. To date, the BTC method has been applied to evaluate cable strength at the Bronx-Whitestone Bridge [1] and Mid-Hudson Bridge [2], in the state of New York, USA.

This report presents the BTC method evaluation of the remaining strength and residual life of the main suspension cables at the Mid-Hudson Bridge in Highland, New York [2].

Section I presents details of the procedures and findings of internal inspection and wire sampling. Section II provides program for laboratory testing of wire properties and test results. Section III presents procedures and results for the main suspension cable strength evaluation. Section IV provides forecast for the main suspension cables residual life. Section V compares the results of cable strength evaluation, using the BTC method, with previous investigations performed by others. Section VI presents sensitivity analysis of key inputs that influence the cable strength. Section VII provides observations, conclusions and recommendations of the BTC method investigation. Appendix A presents a literature review of existing models that have been used for the evaluation of remaining strength of degraded bridge cables. Appendix B provides scatter plots and histograms for input versus simulated probability distributions, for a sample panel.

Mid-Hudson Bridge Background

On August 25, 1930, Governor Franklin D. Roosevelt opened the Mid-Hudson Bridge between Highland, Ulster County to the west, and Poughkeepsie, Dutchess County to the east. When it opened, the bridge provided two lanes of traffic across the Hudson River, one lane in each direction. It also provided a walkway for pedestrian and bicycle traffic. Upon opening, the bridge toll was 80 cents for automobiles and 10 cents for pedestrians and cyclists. In 1933, the Mid-Hudson Bridge was taken over by the New York State Bridge Authority. As more motorists took to the road in the postwar era, the Mid-Hudson Bridge and its approaches have been modified several times to handle increasing traffic loads. The first project came in 1949, when the eastern approach in Poughkeepsie was widened from two to three lanes.

In 1983, the American Society of Civil Engineers designated the Mid-Hudson Bridge as a New York State Historic Civil Engineering Landmark. Since then, projects have been undertaken to ensure the integrity of the bridge for decades to come. In the summer of 1983, the existing two-lane roadway on the bridge was widened to three lanes. Under normal conditions, one lane is open to traffic in each direction, while the center lane is kept closed. During rush hour periods, the center lane is used for the dominant flow of traffic.

The landmark suspension bridge is comprised of a 1,495 foot main span and two 755-foot long side spans. Each main cable is composed of 19 strands, of 320 parallel wires each, totaling 6,080 parallel wires. The individual main cable wire is Gauge 6, 0.192-inch in diameter, with a tolerance of 0.003 inch. With zinc-coating, the final diameter of each wire is 0.196-inch. The wire was manufactured of high strength steel at the Trenton plant of the American Steel and Wire Company, with a specified modulus of elasticity of 27,000 ksi and minimum strength of 215 ksi. The wrapping wire is made of three-ply Gauge 9 soft annealed galvanized steel wire under tension.

Objectives and Scope of Work

The objective of this BTC method investigation is to determine the load carrying capacity and remaining service life of main suspension cables based on the panel openings selected for unwrapping, wedging, internal inspection, sampling and testing.

The BTC method provides the bridge owner a greater understanding of the deterioration mechanisms at work in the cables as well as a comprehensive methodology that provides a higher level of confidence in the estimated remaining cable strength and forecast of residual life of the cable.

Bridge Technology Consulting (BTC) performed the following tasks:

- Evaluation of previous data.
- Selection of panels on each cable to perform internal inspection and sampling.
- Design of random sampling plan for each of the selected panels.
- Testing program for the sampled wires in each panel.
- Determination of the current remaining strength and safety factor of the cables, in each of the investigated panels.
- Forecast of residual service life of the main cable.
- Provided a discussion on the implications of safety factor calculated by the BTC method in comparison with previously calculated safety factors.
- Presented a discussion on differences between models used, and types of testing performed on sampled wires.
- Provided sensitivity analysis of test results.

I. MAIN CABLE INSPECTION AND SAMPLING

Internal inspection of the main cables at the Mid-Hudson Bridge was performed at four panels on each cable, totaling eight panels selected by Bridge Technology Consulting (BTC). The field inspection was conducted between July and August 2009.

Prior to field inspection, a random sampling plan was prepared by BTC. Details of the random sampling plan are presented herein.

I-1. Panel Selection Criterion

The main goal of in-depth cable inspection is to assess the damage in the most deteriorated panels. Assessment of the structural integrity of the cable is achieved by calculating the factor of safety for the eight investigated panels. The panel with the lowest factor of safety will govern the factor of safety for the entire cable. Thus, our objective is to choose the most *at-risk* panels, and not random panels to calculate the safety factor for the cable.

To that end, a study was made of the recorded history of wire breaks along the two cables to identify the most at-risk panels. Based on the profiles of wire breaks observed during previous investigations along the north and south cables, the eight panels, shown in Table I-1, were identified for cable wedging, inspection and sampling.

Table I-1. Panel Opening during 2009 Cable Investigation

Panel Locations (South Cable)*	Panel Locations (North Cable)*
HSS – P.P. 3-4	HSS – P.P. 1-2
HMS – P.P. 61-62	HMS – P.P. 42-43
PMS – P.P. 90-91	PMS – P.P. 77-78
PSS – P.P. 136-137	PSS – P.P. 133-134

* HSS: Highland Side Span
HMS: Highland Main Span
PMS: Poughkeepsie Main Span
PSS: Poughkeepsie Side Span

Due to field conditions that hindered unwrapping of the north cable at P.P. 77N-78N on the Poughkeepsie Main Span, the Contractor requested opening P.P. 89-90 instead. The New York State Bridge Authority approved the Contractor's request.

I-2. Random Sampling and Sample Size Determination

Because it is impractical to sample and test every wire in the cable, we remove only a sample of wires to test in the laboratory. In this way, sampling is done to generate a small group of wires that is as similar to the entire population of wires as possible. With that in mind, two questions arise; how well does the sample represent the larger population from which it was drawn? How closely do the features of the sample resemble those of the larger population? To answer these questions; a definition of sampling methods is introduced first. Sampling methods are classified as either *probability* or *nonprobability*. In probability samples, each member of the population has a known non-zero probability of being selected. Probability methods include random sampling, systematic sampling, and stratified sampling. In nonprobability sampling, members are selected from the population in some nonrandom manner. These include convenience sampling, judgment sampling, quota sampling, and snowball sampling. The advantage of probability sampling is that sampling error can be calculated. Sampling error is the degree to which samples might statistically differ from the population. When inferring to the population, results are reported plus or minus the sampling error. In nonprobability sampling, the degree to which the sample differs from the population remains unknown. Thus random sampling presents the best representation of wire condition throughout the entire bridge cable.

I-2.1 Random Sampling and Practical Considerations

In random sampling, each wire in the available pool of wire samples has an equal and known chance of being selected. Random sampling procedures do not guarantee that the sample is representative, but they do increase the probability that the randomly selected wires will be representative of cable condition. There is a sampling error in the estimated cable strength because not every wire is sampled and tested. The sampling error describes the range that the estimated cable strength is likely to fall within.

Sampling should be limited to provide an acceptable level of error in the estimated cable strength. This is to minimize vulnerabilities introduced in the cable cross-section due to the sampling and removal of wires. This cable investigation is neither the first nor the last opportunity that wire samples will be removed from cable. Therefore, the following practical considerations must be recognized:

- It is not feasible to remove wires too deep in the wedge opening due to clearance problems with surrounding in the wedge opening when cutting, splicing and tightening the splice.
- Even if a deeper wire is pulled with the use of a special tool out of the wedge, access for splicing and re-tightening would be very limited and damage to neighboring wires would become more likely.
- It is therefore our recommendation to minimize damage to main cable and not to remove samples from areas where they could not effectively be replaced and spliced.
- Outer wires are easily accessible, however, inner wires are difficult to reach for the purpose of tightening ferrules, and often a wire would be spliced with zero or small stress. This is evident by the slack condition of many spliced wires observed on suspension bridge cables.

In this plan, we define the *sampling frame* as the accessible group of wires that samples will be randomly selected from. Sampled wires constitute the sample size from which valid conclusions about the entire 6,080 wires are based. This statistical inference is done with the aim of inferring the degraded condition of all wires from those found in the observed sample. By virtue of random selection of wires in the sample, different conditions of wires would be covered in the sample. Random sampling is performed without regard to the visual appearance of wires.

I-2.2 Sampling Size Determination

It is important to evaluate the effect the sample size has on the error in the estimated cable strength. The error results from imprecision associated with estimating nominal cable strength based on a limited number of wire samples. Therefore we set an acceptable target level of error in the estimated cable strength; at a given level of confidence. The sample size of 15 wires in each panel was then determined to achieve the desired target error of 5% at a 95% level of confidence.

I-2.3 Wedge Pattern

The eight-wedge pattern, shown in Figure I-1, was established with NYSBA for this contract, for unwrapping, wedging, wire splicing, recompacting and rewrapping the cable. This wedge pattern is practical and accommodates the parallel investigation, done by others, per the NCHRP Report 534 Guidelines.

I-2.4 Sampling Frame of Random Sample

The sampling frame, which is the pool of wire samples, should be limited to the group of wires that can be accessed for cutting, and splicing back to service load. In this investigation, we define by *sampling frame* the first ten (10) rings of wires; i.e. to a depth of ≈ 2-inches which totals 160 wires, as shown in Figure I-1.

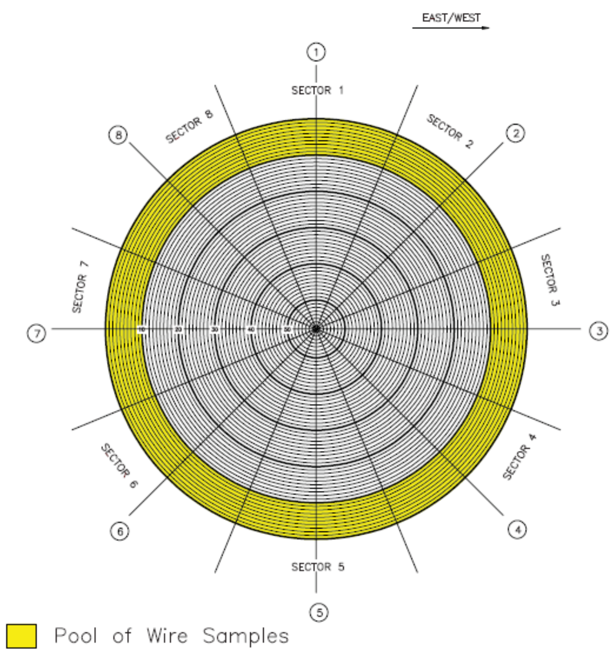

Figure I-1. Eight-Wedge Pattern and Pool of Wire Samples in Cable Cross-Section

Those 160 wires are deemed easily accessible for cutting, splicing and retightening back to service load. The sample size of 15 wires, in each panel, were selected by a novel random sampling technique, utilizing random number generator; such that each wire in the sampling frame has an equal probability of being selected. During inspection, each of the 15 wires was tagged with an I.D. number. Figure I-2 shows a tagged wire with I.D. that reads PP 3-4S, W7/8, R4. This identifies a wire sampled from P.P. 3-4 – HSS, in Wedge #7, Wedge #8 side, Ring # 4.

Figure I-2. Sample Tag in Wedge #7, Wedge #8 Side, Ring # 4,
PP 3-4, HSS, South Cable, per BTC Sampling Plan

The Contractor was instructed to prepare for sampling only the tagged wires; see Figure I-3. Engineers verified that tagged wires matched the wires identified by the BTC sampling plan, as shown in Figure I-4. The Contractor proceeded with splicing the tagged wires; see Figure I-5.

All sampled wires were spliced back to service load in the wire. The sampled wires varied between 9 feet to 12 feet in length. The Contractor had pieces of new wires to splice into the sampled wires, Figure I-6. After connecting the new wire splice to the ends of the sampled wire, the service load is applied on the spliced wire, Figure I-7. As shown in Figure I-8, the splice is tightened to ensure that the spliced wire is not loose. Figure I-9 shows a close-up of splice tightening, where the claws of equipment used to tighten the splice cannot be properly handled deep in the wedge opening. We therefore caution against sampling wires deeper than the group of wires that could be accessed for sampling, splicing, and proper retightening of the spliced wire back to service load. Attempts of sampling wires beyond that accessible depth into the wedge could inflict serious damage and compromise the integrity of zinc coating of adjacent wires, improper splicing and ineffective retightening of the splice, which may develop gaps that act as pockets of water inside the cable. Figure I-10 shows a splice in its final condition after service load has been restored in the spliced wire.

Figure I-3. Preparation of Tagged Wire for Sampling by Contractor

Figure I-4. Verification of Tagged Wires per BTC Sampling Plan, PP 3S-4S, HSS

Figure I-11 shows the form that was given to the inspectors for random sample of wires, in each of the eight wedge openings. The figure shows the wires that were removed from Wedge #7 at Wedge #8 Side, in PP 3-4, HSS, South Cable, per BTC Sampling Plan. Figure I-2 shows tags on Wire #1 and Wire #4, as per the Sampling Plan.

Figure I-5. Contractor's Crew Prepare Tagged Wire for Splicing

Figure I-6. Contractor's Crew Splicing One End of Sampled Wire to A New Wire Piece

Figure I-7. Service Load Application on Spliced Wire

Figure I-8. Tightening of New Wire Splice

Figure I-9. Close-up of Equipment used in Tightening Wire Splice[1]

Figure I-10. Splice in its Final Condition after Restoration of Service Load

[1] Picture was taken by BTC at a different bridge, and shown here for demonstration of wire splicing tools.

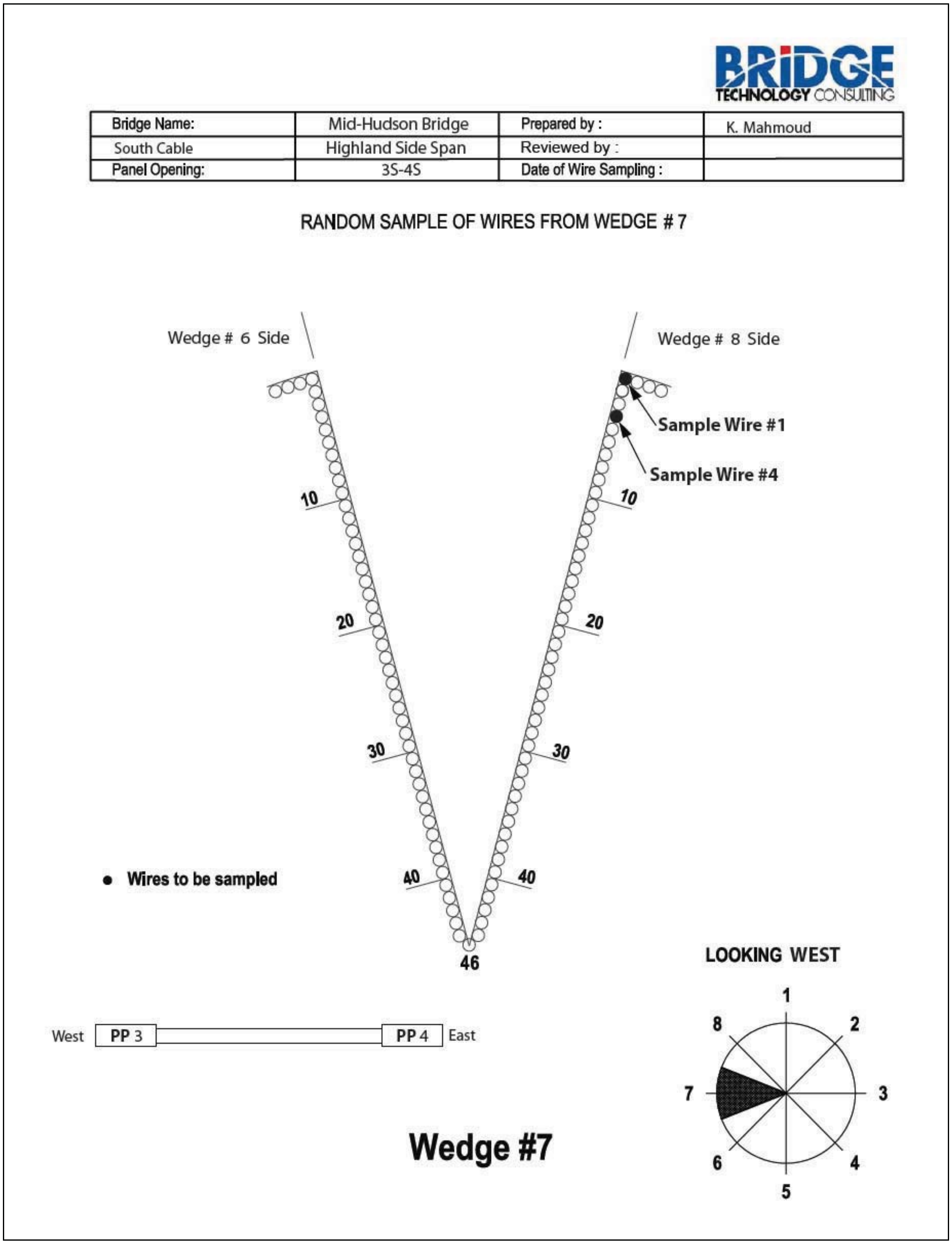

Figure I-11. Random Sampling of Wires from Wedge #7, P.P. 3S-4S – HSS, South Cable

I-3. Inspection Procedures

An access platform was constructed along the full length of each of the eight investigated panels. Internal inspection was performed by driving plastic wedges along four planes. After the removal of the Gauge 9 wrapping wire in each panel, the cable was wedged with an eight-wedge pattern as shown in Figure I-1, numbered in circles from 1 to 8.

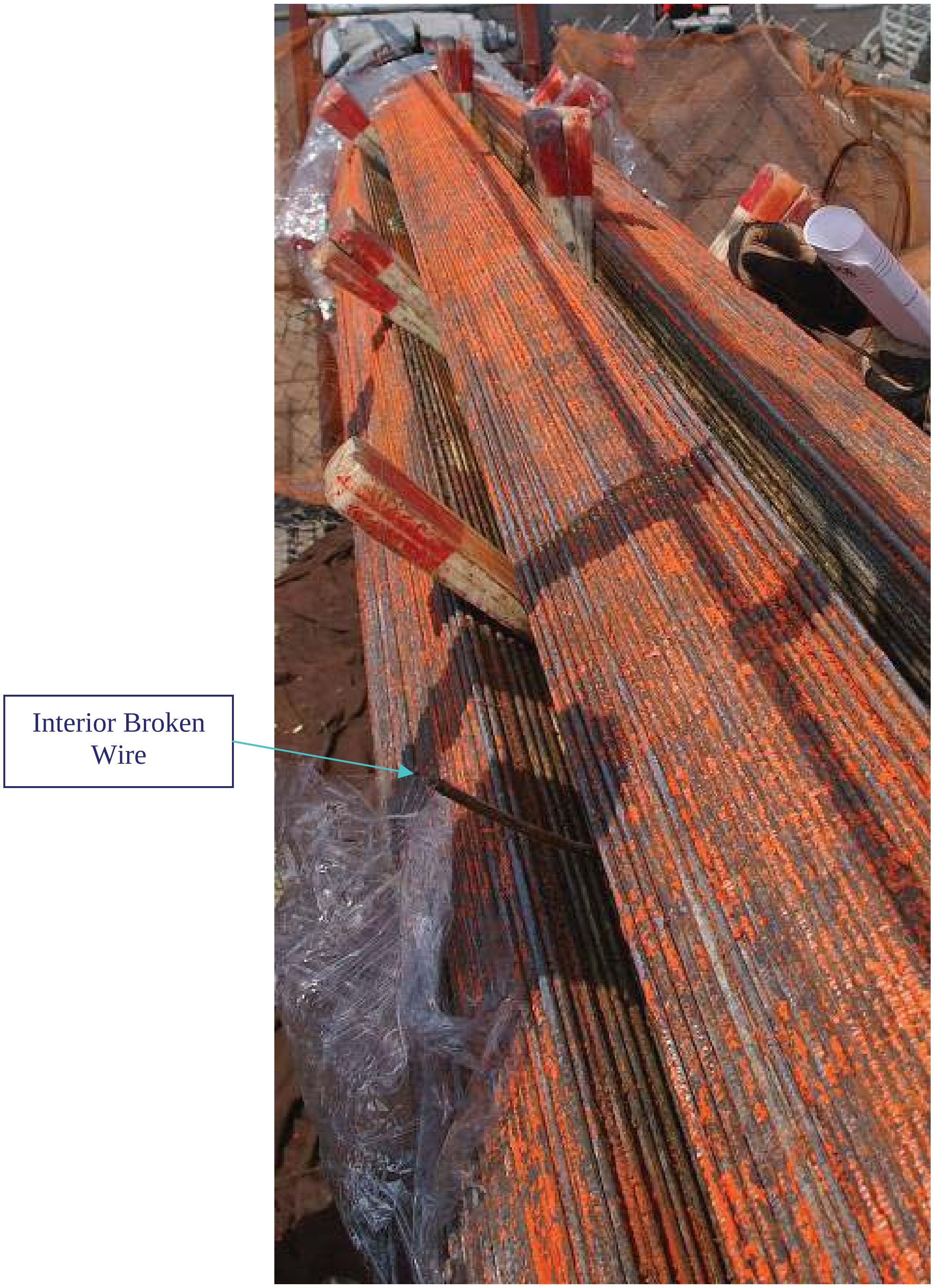

Figure I-12. Wedges Driven to the Center of the Cable, Interior Broken Wire is shown

The Contractor, utilizing plastic wedges driven to the center of the cable, wedged the cable for internal inspection, Figure I-12. As shown in the photo, stacks of wedges were driven to allow for proper inspection and access to splice sampled and broken wires. Figure I-12 shows an interior broken wire.

Visual evaluation of corrosion stages was documented in each panel, for the purpose of a parallel evaluation conducted by others in accordance with the NCHRP Report 534 Guidelines [3]. This evaluation, which was first introduced by Hopwood and Havens in 1984 [4, 5], relies on visual-based assessment of corrosion damage to the wire surface into four stages of corrosion, see Figure I-13. The four stages of corrosion are defined as follows:

Stage 1: the zinc coating of wires is oxidized to form zinc hydroxide, known as “white rust”.
Stage 2: the wire surface is completely covered by white rust.
Stage3: appearance of a small amount (20-30% of wire surface area) of ferrous corrosion due to broken zinc coating.
Stage 4: the wire surface is completely covered with ferrous corrosion.

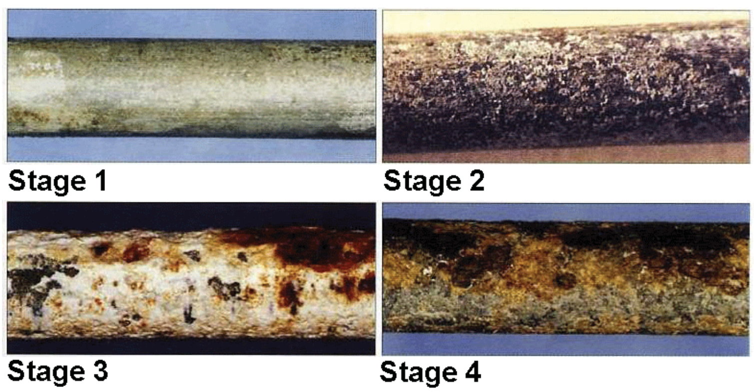

Figure I-13. The Four Stages of Corrosion per NCHRP Report 534 Guidelines

I-4. Inspection Findings of Degradation:

The BTC method identifies proportion of broken wires based on wires found broken during inspection in each panel. Further degradation analysis is performed under wire testing as shown in Section II.

I-4.1 Broken Wires

The general visual condition of both cables indicates the presence of active degradation as evident by corrosion and observed wire breaks. Under this investigation, 64 wires were observed broken in seven of the eight investigated panels, see Table I-2. The vast majority of interior broken wires were found in the upper half of the cable circumference.

Table I-2. Observed Broken Wires

Panel Location	Observed Broken Wires		Total Number of Broken Wires
	Outer Ring	Interior Wires	
1N-2N-HSS	0	5	5
42N-43N-HMS	8	8	16
89N-90N-PMS	0	3	3
133N-134N-PSS	0	14	14
3S-4S-HSS	8	10	18
61S-62S-HMS	0	0	0
90S-91S-PMS	0	4	4
136S-137S-PSS	1	3	4

A total of 38 broken wires were found in the four inspected panels on the north cable, eight (8) of which were found along the exterior ring and the other 30 broken wires were found in the interior rings of the cable. Along the south cable, a total of 26 broken wires were found, nine (9) of which along the exterior ring and 17 were found in the interior of the cable. A breakdown of broken wires is shown in Table I-2.

Since the last inspection in 2003/2004, PP 133N-134N, PSS, has shown the most active degradation with increasing rate of interior broken wires. Broken wires in the outer ring are accessible and identified during inspection. As will be shown later, the probability of broken wires, p_0, is assessed based on the observed broken wires in the interior rings of the cable. Therefore this analysis considers rate of interior wire breaks whenever the number of interior broken wires is available.

<u>I-4.2 Wire Samples Corrosion Grade Classification</u>

During this investigation, 15 wire samples were removed from each of the eight panels for testing, totaling 120 wire samples. To satisfy a parallel evaluation done by others in accordance with the NCHRP Report 534 Guidelines; one additional wire was sampled from each of two panels along the north cable; PP 1N-2N-HSS and PP 89N-90N-PMS. Table I-3 shows the stage of corrosion, per NCHRP Guidelines, for the wires sampled in each panel. As mentioned earlier, wire samples were removed in accordance with BTC random sampling plan. The BTC method's random sampling plan and assessment of remaining cable strength are independent of visual-based evaluation of corrosion on wire surface, as defined by NCHRP Report 534 Guidelines. However, corrosion stages per NCHRP Report 534 Guidelines, which are assigned and used by others in a parallel evaluation, are shown for later discussion of test results and models used in the current and previous investigations.

The following section describes the testing program conducted on the wire samples in accordance with the Testing Plan designed by BTC.

Table I-3. Corrosion Classification in Each Investigated Panel (per NCHRP Guidelines)

Location	**Number of Wire Samples**				**Total**
	Stage 1	**Stage 2**	**Stage 3**	**Stage 4**	
1N-2N-HSS	0	6	8	2	16
42N-43N-HMS	0	9	5	1	15
89N-90N-PMS	0	2	9	5	16
133N-134N-PSS	1	9	2	3	15
3S-4S-HSS	0	6	9	0	15
61S-62S-HMS	0	2	12	1	15
90S-91S-PMS	0	2	11	2	15
136S-137S-PSS	2	1	12	0	15
Total	**3**	**37**	**68**	**14**	**122**

II. LABORATORY TESTING OF WIRE PROPERTIES

The 122 wire samples removed from the two cables were taken for testing to determine mechanical and chemical properties, as follows:

- Enhanced Tensile Strength Test on Standard Wire Specimens, 18-inch in length. In enhanced tensile strength test, the stress strain curve is provided up to ultimate elongation of the wire specimen.
- Tensile Strength Test on Long Wire Specimens, 72-inch in length.
- Fractographic and Scanning Electron Microscope (SEM) Evaluation.

BTC sampling plan has the following breakdown of 15 test samples, in each of the eight investigated panels:

Each wire was cut as follows:

- One long specimen, 72-inchin length.
- Two to four standard specimens, 18-inch in length. Number of standard specimens depends on the length of wire which varies between 9 ft to 12 ft. Breakdown of the number of 18-inch standard specimens, in each of the eight investigated panels, is shown in Table II-1.

Tension tests on 18-inch standard specimens and 72-inch long specimens were conducted at the ATLSS Center of Lehigh University. The fractographic and SEM examination were performed at Lucius Pitkin, Inc.

Figure II-1 shows the layout of BTC testing plan, for each of the eight investigated panels.

The following tests typically provide information regarding chemical composition of the steel wire, corrosion analysis of corrosion products and integrity of zinc-coating on wire surface:

- Chemical Analysis to determine percentages of carbon, silicon, sulfur, phosphorous, manganese, copper, nickel, chromium, molybdenum and aluminum. It is important to conduct this analysis at least once because variations in the carbon content may explain unusual variations in tensile strength of wire samples.
- Corrosion Analysis to determine the presence of chlorides, sulfates and nitrates that may contribute to corrosion of wire.
- Zinc-Coating Tests:
    - Weight of Zinc-Coating Test; specified in ASTM A90. The average weight of zinc may be converted to an average remaining zinc-coating thickness in a unit length, and used to predict depletion of zinc-coating.
    - Preece Test; specified in ASTM A239. This test determines the uniformity of zinc-coating on wire surface.

Chemical Analysis, Corrosion Analysis and Preece Tests were performed on wire specimens in previous investigations and were not conducted during this investigation.

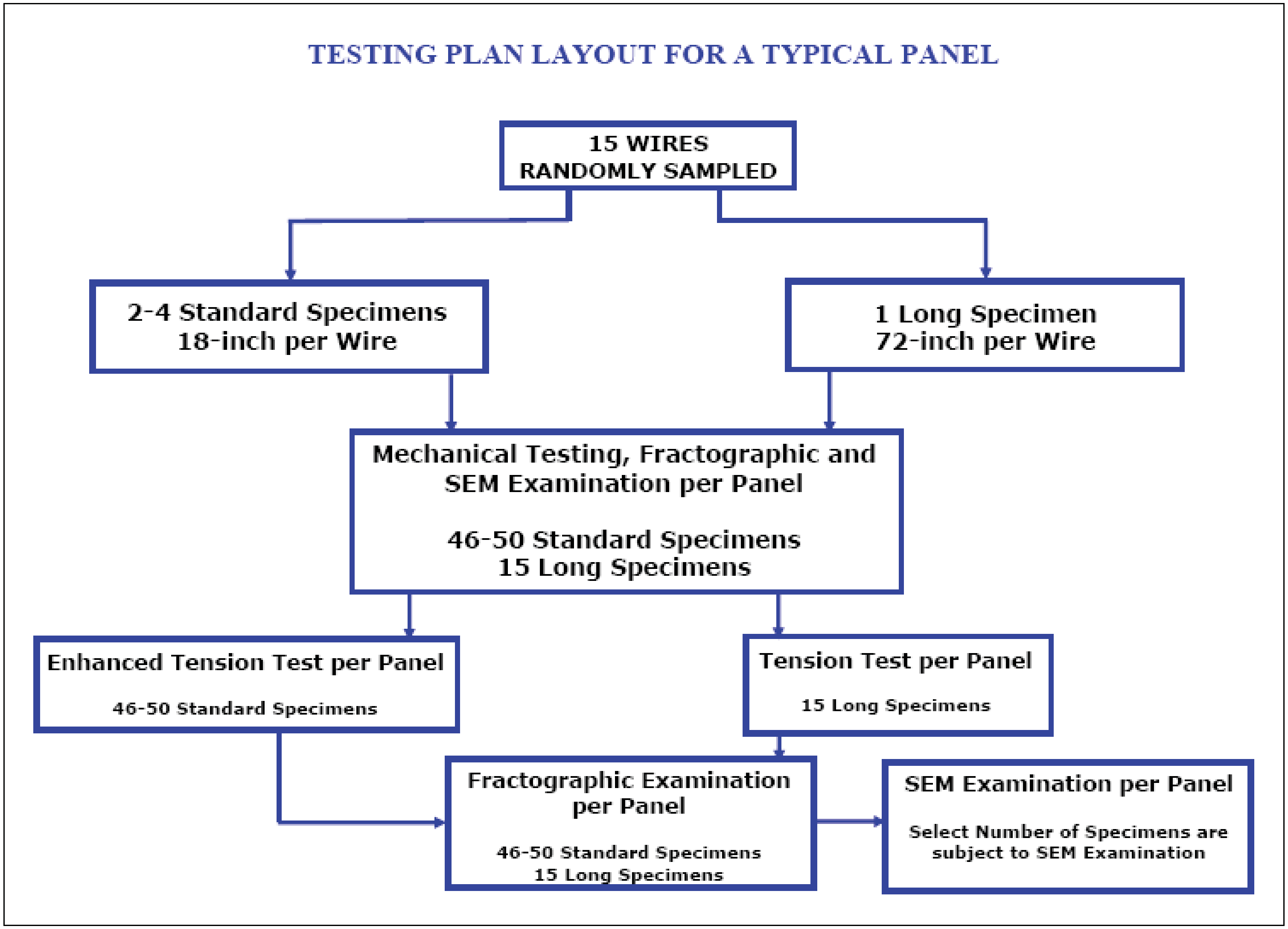

Figure II-1. BTC Testing Plan for Sample Wires from Eight Investigated Panels

II-1. Enhanced Tensile Test on Standard Wire Specimens (18-inch)

A total of 383 eighteen inch in length tension specimens were tested, at the ATLSS Center of Lehigh University, in a computer controlled 50 kip capacity MTS servo-hydraulic test machine fitted with hydraulic wedge grips for gripping the wire specimens. A pair of linear displacement sensors was attached to the wire specimen at 10-inchgage length to measure tensile elongation, see Figure II-2.

Figure II-2. General View of 18-inch Wire Specimen Tensile Test Setup

II-1.1 Description of Enhanced Tensile Test on Standard Wire Specimens

A total of 383 standard specimens (18-inch) were tested with the following breakdown in each of the eight investigated panels, as shown in Table II-1.

Table II-1. Breakdown of Standard Specimens (18-inch)

Location	**No. of 18-inch Wire Specimens**
1N-2N-HSS	50
42N-43N-HMS	47
89N-90N-PMS	50
133N-134N-PSS	48
3S-4S-HSS	47
61S-62S-HMS	48
90S-91S-PMS	47
136S-137S-PSS	46
Total	**383**

Specimens were statically loaded at a constant displacement rate of 0.1 in./min. to failure. Load, strain, and crosshead displacement was continuously recorded with a Campbell Scientific CR9000 Data Logger at a sample rate of 5 per sec. To remove the helical wire curvature an initial pre-load corresponding to a stress of approximately 10 ksi was applied to the wire specimen prior to attaching the extensometer, as per ASTM A586. Figure II-3 shows a typical stress strain curve resulting from enhanced tension test.

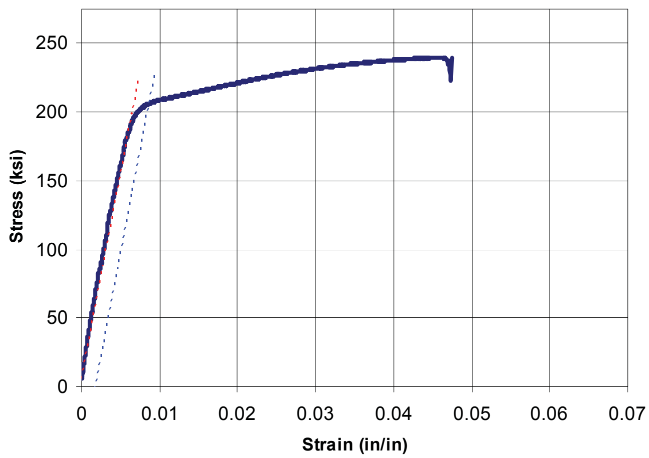

Figure II-3. Typical Stress Strain Curve for Enhanced Tensile Test on a Standard Wire Specimen

II-1.2 Results of Enhanced Tensile Test on Standard Wire Specimens

Tables II-2 and II-3 provide summary for test data statistics for intact wires removed from the eight investigated panels along the north and south cables, respectively. Test data provides values, in each panel, for the ultimate strength, σ_u, ultimate strain, ε_u, Young's Modulus, E, and the yield strain, ε_e.

Table II-4 provides the breakdown of mechanical properties per corrosion stage for the 122 wire samples. Tables II-5 and II-6 provide the breakdown of wire properties per corrosion stage in each panel for the north and south cables, respectively. The BTC method does not employ the stages of corrosion in the evaluation of remaining strength of the cable. Corrosion stages data is provided for comparison purposes only.

As shown in Tables II-5 and II-6, there is little correlation, if any, between degradation of cable strength and visually-evaluated corrosion on wire surface. For seven of the eight investigated panels, per NCHRP Guidelines, the ultimate elongations for Stages 3 and 4 are higher than the ultimate elongation for Stage 2; see Tables II-5 and II-6. Further, for the eight investigated panels, per NCHRP Guidelines, the ultimate strengths for Stage 4 is higher than that for Stage 3, the ultimate strength for Stage 3, is higher than that for Stage 2, or that the ultimate strength for Stage 2, is higher than that for Stage 1; see Tables II-5 and II-6. These observations illustrate the contradiction that results from relying on the subjective visual evaluation of corrosion stages. The BTC method conducts sampling without regard to the visual appearance of wires, and strength evaluation based on measured properties of tested wires.

Table II-2. Summary of Data Statistics for Intact Sampled Wires along the North Cable

Data	Sample Test Statistics (PP 1N-2N)			SampleStatistics (PP 42N-43N)		
Variable	Mean	Std. Dev.	Coeff. of Variation	Mean	Std. Dev.	Coeff. of Variation
σ_u (ksi)	233.300	7.480	0.032	233.183	9.351	0.040
ε_u (%)	4.096	0.766	0.187	3.958	0.672	0.170
E (ksi)	28799	955	0.033	28373	761	0.027
ε_e (%)	0.690	0.030	0.043	0.698	0.031	0.044

Data	SampleStatistics (PP 89N-90N)			SampleStatistics (PP 133N-134N)		
Variable	Mean	Std. Dev.	Coeff. of Variation	Mean	Std. Dev.	Coeff. of Variation
σ_u (ksi)	233.316	9.812	0.042	233.934	7.788	0.033
ε_u (%)	4.153	0.927	0.223	4.360	0.691	0.158
E (ksi)	28456	1004	0.035	28238	1140	0.040
ε_e (%)	0.693	0.029	0.042	0.694	0.034	0.049

Table II-3. Summary of Data Statistics for Intact Sampled Wires along the South Cable

Data Variable	Sample Test Statistics (PP 3S-4S)			Sample Statistics (PP 61S-62S)		
	Mean	Std. Dev.	Coeff. of Variation	Mean	Std. Dev.	Coeff. of Variation
σ_u (ksi)	236.971	9.712	0.041	237.139	9.464	0.040
ε_u (%)	4.878	0.860	0.176	4.926	0.750	0.152
E (ksi)	28655	1368	0.048	28647	1151	0.040
ε_e (%)	0.699	0.046	0.066	0.692	0.035	0.051

Data Variable	Sample Statistics (PP 90S-91S)			Sample Statistics (PP 136S-137S)		
	Mean	Std. Dev.	Coeff. of Variation	Mean	Std. Dev.	Coeff. of Variation
σ_u (ksi)	237.461	11.185	0.047	231.853	8.670	0.037
ε_u (%)	4.193	0.545	0.130	4.048	0.721	0.178
E (ksi)	28763	1060	0.037	29422	1296	0.044
ε_e (%)	0.693	0.031	0.045	0.669	0.036	0.054

Table II-4. Breakdown of Sampled Wire Properties per Corrosion Stage (Shown for Illustration Purposes)

Corrosion Stage	Ultimate Strength (1) Mean (ksi)	Ultimate Strain (1) Mean (%)	Number of Wire Samples
Stage 1	234.46	4.84	3
Stage 2	233.76	4.20	37
Stage 3	235.45	4.39	65
Stage 4	232.42	4.31	6
Stage 5 (2)	191.63	1.44	11

(1) Ultimate Strength and Ultimate Strain mean values were calculated for each corrosion stage based on corrosion classifications recorded on wire sample tags during field inspection.

(2) Stage 5 defines wires that contain preexisting cracks, as per definition of NCHRP Report 534 Guidelines.

Table II-5. Breakdown of Sampled Wire Properties per Corrosion Stage in Each Panel, North Cable

Panel Location	**Corrosion Stage**	**Avg. Ultimate Strength (ksi)**	**Average Ultimate Strain (%)**	**Panel Location**	**Corrosion Stage**	**Avg. Ultimate Strength (ksi)**	**Average Ultimate Strain (%)**
PP 1N-2N	Stage 1	-	-	**PP 42N-43N**	Stage 1	-	-
	Stage 2	234.80	3.75		Stage 2	234.20	3.95
	Stage 3	232.30	4.16		Stage 3	230.70	4.07
	Stage 4	233.70	4.95		Stage 4	236.40	4.13

Panel Location	**Corrosion Stage**	**Avg. Ultimate Strength (ksi)**	**Average Ultimate Strain (%)**	**Panel Location**	**Corrosion Stage**	**Avg. Ultimate Strength (ksi)**	**Average Ultimate Strain (%)**
PP 89N-90N	Stage 1	-	-	**PP 133N-134N**	Stage 1	233.14	4.96
	Stage 2	226.60	3.35		Stage 2	236.30	4.39
	Stage 3	234.90	4.41		Stage 3	231.80	4.55
	Stage 4	232.50	4.34		Stage 4	226.40	3.62

Table II-6. Breakdown of Sampled Wire Properties per Corrosion Stage in Each Panel, South Cable

Panel Location	Corrosion Stage	Avg. Ultimate Strength (ksi)	Average Ultimate Strain (%)	Panel Location	Corrosion Stage	Avg. Ultimate Strength (ksi)	Average Ultimate Strain (%)
PP 3S-4S	Stage 1	-	-	PP 61S-62S	Stage 1	-	-
	Stage 2	234.50	5.23		Stage 2	223.20	4.44
	Stage 3	238.70	4.63		Stage 3	238.30	4.96
	Stage 4	-	-		Stage 4	245.60	5.41

Panel Location	Corrosion Stage	Avg. Ultimate Strength (ksi)	Average Ultimate Strain (%)	Panel Location	Corrosion Stage	Avg. Ultimate Strength (ksi)	Average Ultimate Strain (%)
PP 90S-91S	Stage 1	-	-	PP 136S-137S	Stage 1	235.30	4.76
	Stage 2	236.30	3.63		Stage 2	214.20	3.70
	Stage 3	238.40	4.29		Stage 3	232.20	3.95
	Stage 4	231.60	3.93		Stage 4	-	-

II-2. Tensile Test on Long Wire Specimens (72-inch)

The purpose of testing long specimens is to identify the presence of cracks in test specimens. Testing long specimens, in addition to standard 18-inch long specimens, increases the probability of finding cracks in test specimens. This is because in standard specimens, only about 12-inch of the specimen length is outside the grips of testing machine. Therefore cracks might be missed if tensile test is limited to standard specimens.

II-2.1 Description of Tensile Test on Long Wire Specimens

A total of 122 wire specimens, each of 72-inch in length, were tested, at the ATLSS Center of Lehigh University, in a computer controlled Satec 600 kip capacity universal test machine fitted with hydraulic wedge grips for gripping the wire specimens. A pair of linear displacement sensors was attached to the wire specimen at 10-inch gage length to measure tensile elongation, see Figure II-4. Due to the long specimen length and risk of damage to the extensometer at fracture it was removed prior to fracture. Load-strain data was obtained up to a strain of 0.02. This allowed for determination of the yield point without subsequent risk to the extensometer. Specimens were statically loaded at a constant displacement rate of 0.4 in./min. to failure to produce a comparable strain rate as applied in the 18-inch length specimens. Load, strain, and crosshead displacement were recorded with a Campbell Scientific CR9000 Data Logger at a sample rate of 5 per sec. Table II-7 shows the breakdown of long specimens per panel.

Table II-7. Breakdown of Long Wire Specimens Tested for Presence of Preexisting Cracks

Location	No. of 72-inch Wire Specimens in each Panel
1N-2N-HSS	16
42N-43N-HMS	15
89N-90N-PMS	16
133N-134N-PSS	15
3S-4S-HSS	15
61S-62S-HMS	15
90S-91S-PMS	15
1N-2N-HSS	15
Total	**122**

II-2.2. Results of Tensile Test on Long Wire Specimens

The fracture surfaces of all 122 wire specimens were examined under stereomicroscopic at Lucius Pitkin. Six specimens from the 122 wire specimens, in five panels, exhibited preexisting cracks. The wires with the preexisting cracks in the 72-inch long specimens are shown in Table II-8.

Table II-8. Preexisting Cracks in 72-inch Wire Specimens

PP	Cracked 72-inch Wire Specimens	Ultimate Strength (ksi)	Crack Depth (inch)
1N-2N-HSS	L62	148.60	0.067
1N-2N-HSS	L71	224.50	0.003
89N-90N-PMS	L95	233.10	0.006
133N-134N-PSS	L117	111.30	0.028
3S-4S-HSS	L8	210.30	0.008
90S-91S-PMS	L38	193.60	0.017

Following the tensile tests, the fracture surfaces of all 122 specimens were examined under stereomicroscope for preexisting cracks, as shown in the following section. The crack depths shown in Table II-8 are used, along with crack depth measured in the 18-inch standard specimens, which contain preexisting cracks; see Table II-9, to evaluate the average ultimate strength of cracked wires as shown later in this report.

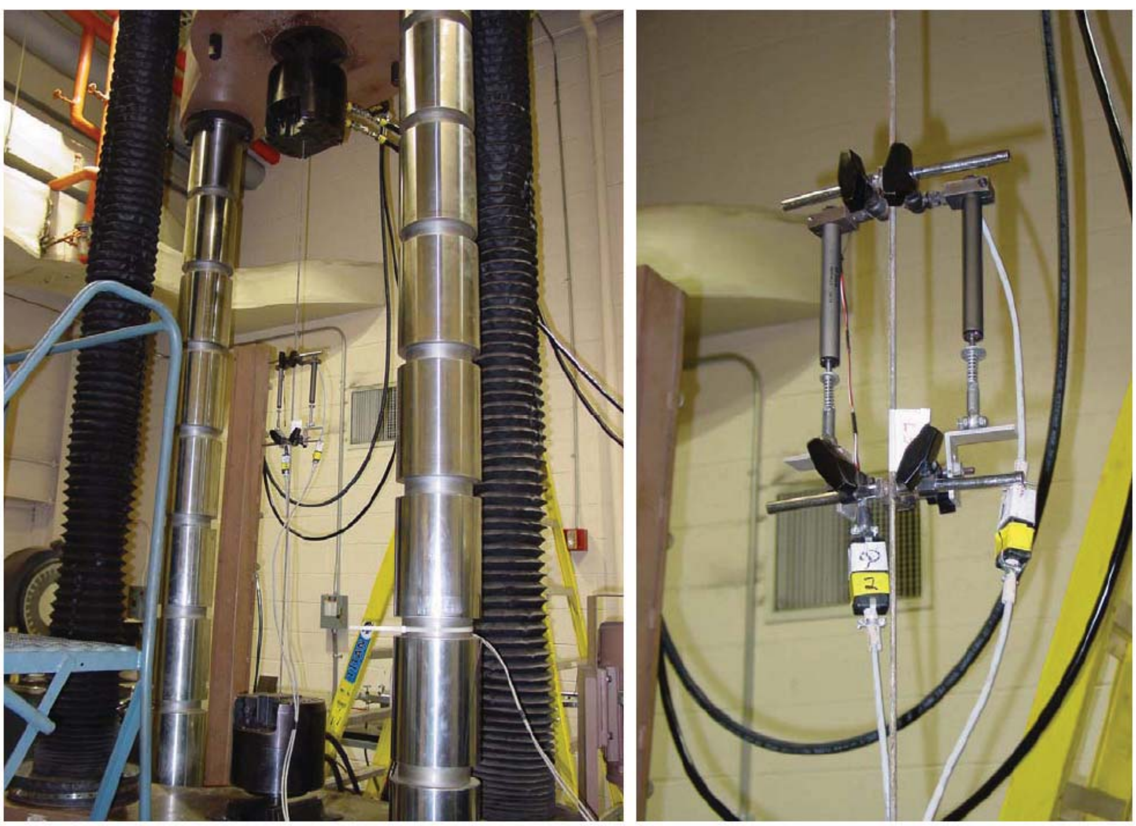

Figure II-4. General View of 72-inch Wire Specimen Tensile Test Setup

II-3. Fracture Toughness Test

For a brittle material, with high yield strength, such as that of suspension bridge wire, the presence of even a small crack is likely to trigger fracture. The occurrence of fracture depends on crack size and orientation, material properties and applied loads. Therefore fracture mechanics assessment is crucial to obtain the strength of cracked wires.

In the traditional approach to structural design, the two major variables under consideration are the material strength and the applied stress. The component is assumed to be adequate if its strength is greater than the expected applied stress. Such an approach guards against brittle fracture through the introduction of a safety factor. In the presence of a crack, fracture can occur at stresses below the material's yield strength and even at the allowable design stress level. In fracture analysis, an additional variable to consider is the crack size, and the fracture toughness, K_C, replaces the material strength as the relevant material property [6]. Fracture toughness is a property which describes the ability of a material containing a crack to resist brittle fracture. With this definition, the three variables, namely; applied stress, crack size, and the fracture toughness constitute the fracture mechanics triangle. Fracture-based analysis provides a mathematical relationship between the three variables, which defines a fracture driving force represented by the stress field ahead of a sharp crack, which is defined by the stress intensity factor, K_I. The wire material will sustain a crack without brittle fracture as long as the applied stress intensity factor, K_I, is below its critical value, the fracture toughness, K_C. With that rationale, fracture toughness is an indispensable parameter in the evaluation of cracked wires.

Bridge Technology Consulting (BTC) presented a proprietary method for the first experimental and analytical evaluation of fracture toughness of the 5-mm suspension bridge wire. Utilizing its proprietary methodology, BTC performed the first identification of the fracture toughness of degraded suspension cable bridge wire at the Mid-Hudson Bridge cable with funding from the New York State Bridge Authority under separate contract [7]. Fracture toughness testing was performed on wire specimens sampled during the 2003/2004 cable inspection and were delivered to the testing laboratory in spools after being removed from the bridge cable. Short samples of 24-inch in length were cut to perform the toughness tests at different temperatures. The tests were conducted at room temperature, 32^{o}F, 0^{o}F, and -30^{o}F. The experimental data for pre-cracked degraded wire samples gives an average value of about 59.50 ksi $\sqrt{in}$ for the wire fracture toughness. The fracture toughness value identified through this test is used to determine the average ultimate strength of set of cracked wires, $\sigma_{ult.\,cr.}$, as follows:

$$\sigma_{ult.cr.} = \frac{(K_c)}{Y(\frac{a}{D})\,.\,\sqrt{\pi.a_c}} \qquad \text{(II-1)}$$

where $\left(K_c\right)$ is the effective fracture toughness, a_c is the critical crack depth and $Y(\frac{a}{D})$ is the crack geometry factor.

II-4. Fractographic Evaluation of Fracture Surfaces

The words “crack” and “flaw” are used sometimes interchangeably. However, while all cracks and corrosion pits can be considered to be flaws (or defects), not all flaws or corrosion pits are cracks. The distinction is in both the sharpness of the crack tip and in the direction of defect growth. A crack is defined as a flaw with very small radius of curvature at its tip, which initiates on the wire outer surface and progresses transversely toward the center of wire, in a direction orthogonal to the longitudinal axis of the wire. This configuration defines mode-I (tensile) cracking where the stress direction is perpendicular to the faces of the crack. As such corrosion pits, which propagate along the longitudinal axis of the wire, should not be considered cracks. Therefore much care is needed to confirm the presence of preexisting cracks through microscopic examination, which demonstrates that zinc coating on the outer surface of wire typically depletes and the crack initiates at a surface deficiency. Cracking then progresses transversely with little associated plastic deformation, as is characteristic of stress corrosion cracking. Microscopic examination also reveals that preexisting cracks exhibit beach marks, as is characteristic of fatigue crack growth during service.

Figure II-5. General view of wire specimens, as delivered to LPI, after tensile testing

In the BTC method, microscopic examination is performed on all fracture surfaces of the entire set of sampled wires to identify cracks.

BTC retained Lucius Pitkin, Inc. (LPI) to provide fractographic examination for all fracture surfaces of the entire set of tested wires. The fracture surfaces of 383 18-in. and 122 72-in. long specimens were examined under stereomicroscope to identify preexisting cracks. General view of arbitrary six wire specimens, as delivered to LPI, is shown in Figure II-5.

II-4.1 Stereomicroscope Evaluation of Fracture Surfaces

Twenty of the 505 wire specimens exhibited preexisting cracks. The breakdown of 18-inch and 72-inch wire specimens with preexisting cracks from each panel are given in Table II-9, along with corresponding ultimate strength and crack depths. It should be noted that the average strength of cracked wires, per the BTC method, is evaluated based on the fracture toughness and crack depth of degraded wires, following principles of fracture mechanics.

Three wires with different crack depths were examined at high magnification. The wire specimens were ultrasonically cleaned in an alcohol-acetone solution prior to examination. Photographs of these wire surfaces near the fracture and the fracture surfaces are shown in Figures II-6 through II-8.

Table II-9. Preexisting Cracks in 18-inch Wire and 72-inch Wire Specimens

Location	**Cracked 72-inch Specimens** (1)	**Cracked 18-inch Specimens** (2)	**Ultimate Strength (ksi)**	**Ultimate Strain (%)** (3)	**Crack Depth (inch)**	**No. of Cracked Wires**
1N-2N-HSS		62-1	220.70	3.01	0.018	2
	L62		148.60	-	0.067	
	L71		224.50	-	0.003	
42N-43N-HMS	-	-	-		-	0
89N-90N-PMS		94-2	170.52	0.73	0.026	3
		102-1	140.43	0.51	0.064	
	L95	-	233.10	-	0.006	
133N-134N-PSS		117-1	195.86	0.94	0.027	3
		117-3	214.81	1.83	0.026	
		118-1	208.50	2.80	0.018	
		122-3	197.47	0.95	0.023	
	L117	-	111.30	-	0.028	
3S-4S-HSS		8-1	181.78	0.78	0.033	1
		8-2	173.10	0.72	0.034	
		8-3	173.49	0.69	0.037	
	L8	-	210.30	-	0.008	
61S-62S-HMS	-	25-2	222.85	2.00	0.019	1
		25-3	196.81	0.79	0.027	
		25-4	200.38	1.06	0.021	
90S-91S-PMS		38-3	214.56	3.3	0.012	1
	L38		193.60	-	0.017	
136S-137S-PSS	-	-	-	-	-	0
Total/Average	**6**	**14**	**191.63**	**1.44**	**≈ 0.026**	**11**

(1) Notations indicate 72-inch long specimens; therefore L62 is the long specimen taken from wire No. 62.
(2) Notations indicate 18-inch wire specimens; for instance 62-1 is specimen No. 1 taken from wire No. 62.
(3) Ultimate strain was measured only for 18-inch long standard specimens.

Figure II-6. Surface (top) and fracture surface (bottom) of wire W94-2
with preexisting crack

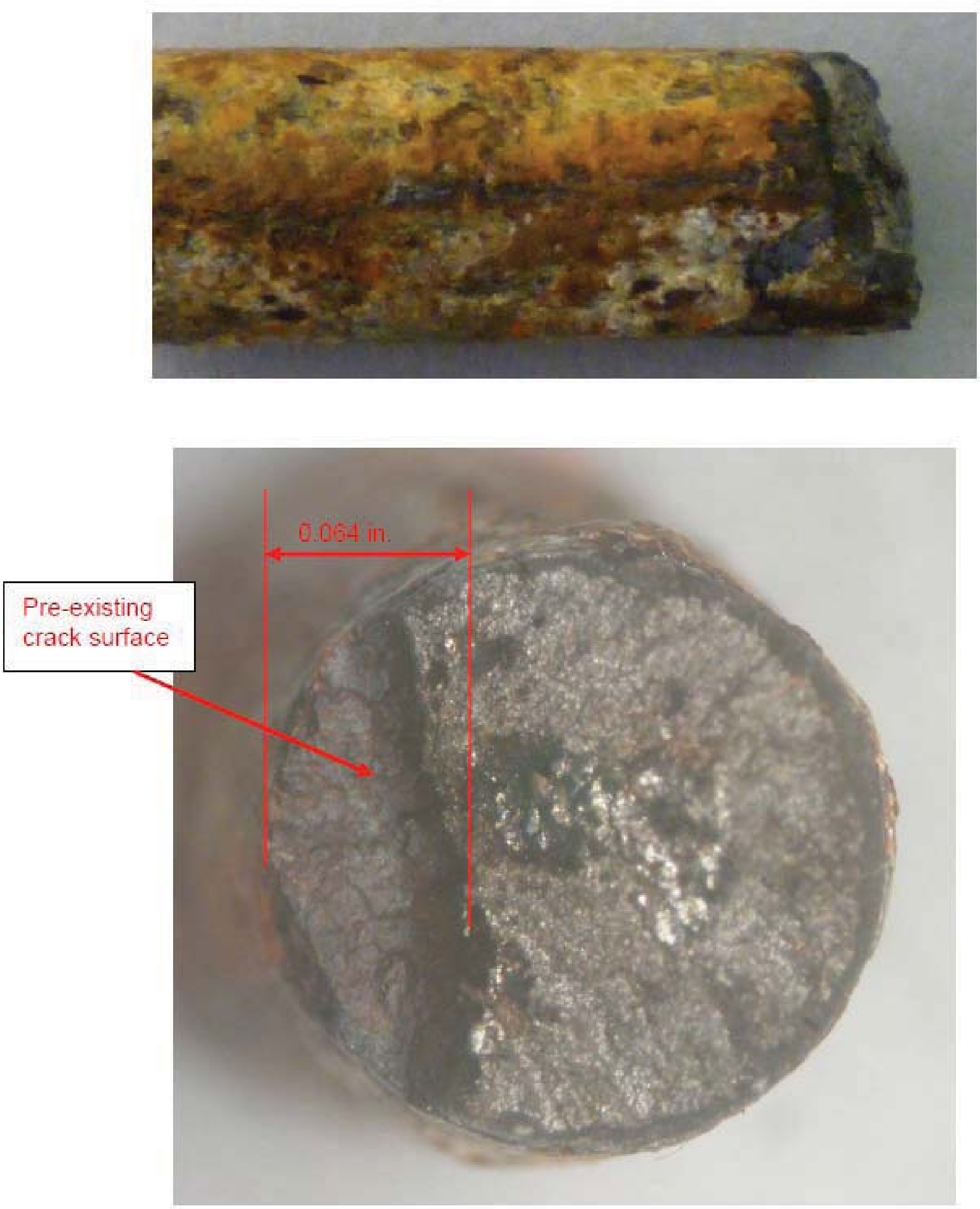

Figure II-7. Surface (top) and fracture surface (bottom) of wire W102-1 with preexisting crack

Figure II-8. Surface (top) and fracture surface (bottom) of wire W8-3 with preexisting crack

Specimens 62-1, 71-1, L62, L63, L65, L68, L69 and L71, in PP 1N-2N, along the north cable, were reported, by others, to contain preexisting cracks. As such, six (6) wires out of 16 wire samples in PP 1N-2N would count as cracked, resulting in 37.5% of cracking in that panel. This would be cracking in the panel itself, without effect of adjacent panels.

Further examination of this group of wires was conducted during BTC Fractographic Evaluation Study. The fractographic evaluation revealed that wire samples L63, L65, L68, L69 and W71-1 exhibit deep pitting located longitudinally near the fracture surfaces, which exhibited predominately necking-down or shear profile, as shown in Figures II-9 through II-13. SEM evaluation revealed that the visible dark areas, near the fracture surfaces, were corrosion pitting and not preexisting cracks, as shown in Figure II-14. Wire specimen W95-2, from PP 89N-90N, was classified cracked by others. BTC further investigation revealed that the wire specimen contains deep pitting and not a preexisting crack; see Figure II-15. It is worth noting that wire specimen W95-2 exhibits ultimate strength of 242.9 ksi and ultimate strain of 4.20%, which are inconsistent with the properties of a specimen with preexisting crack.

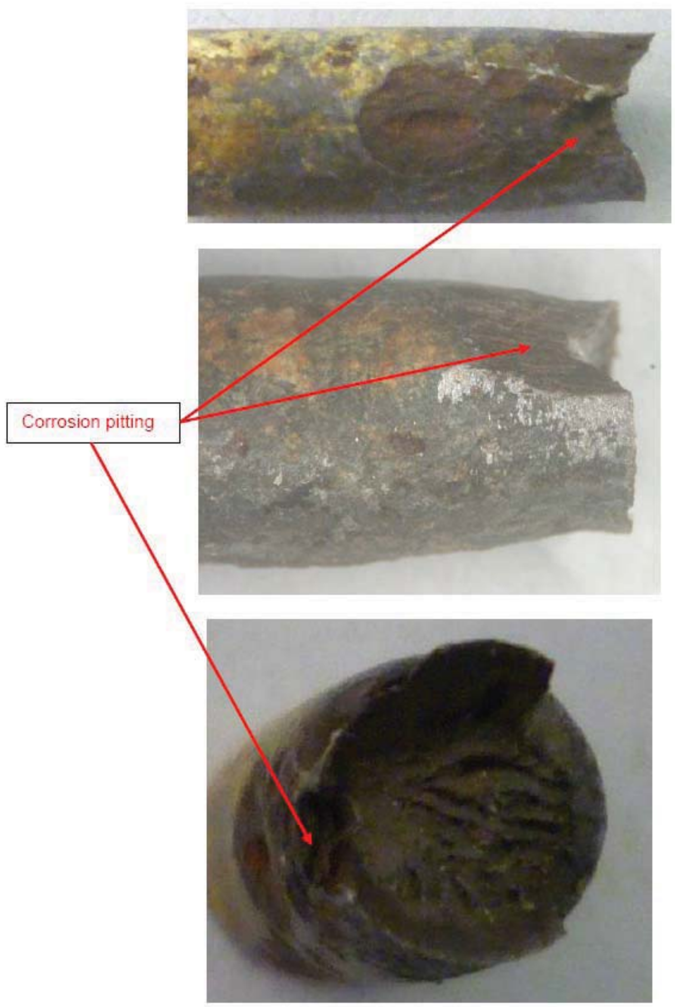

Figure II-9. Surface (top) and fracture surface (bottom) of wire L63

Figure II-10. Surface (top) and fracture surface (bottom) of wire L65

Figure II-11. Surface (top) and fracture surface (bottom) of wire L68

Figure II-12. Surface (top) and fracture surface (bottom) of wire L69

Figure II-13. Surface (top) and fracture surface (bottom) of wire W71

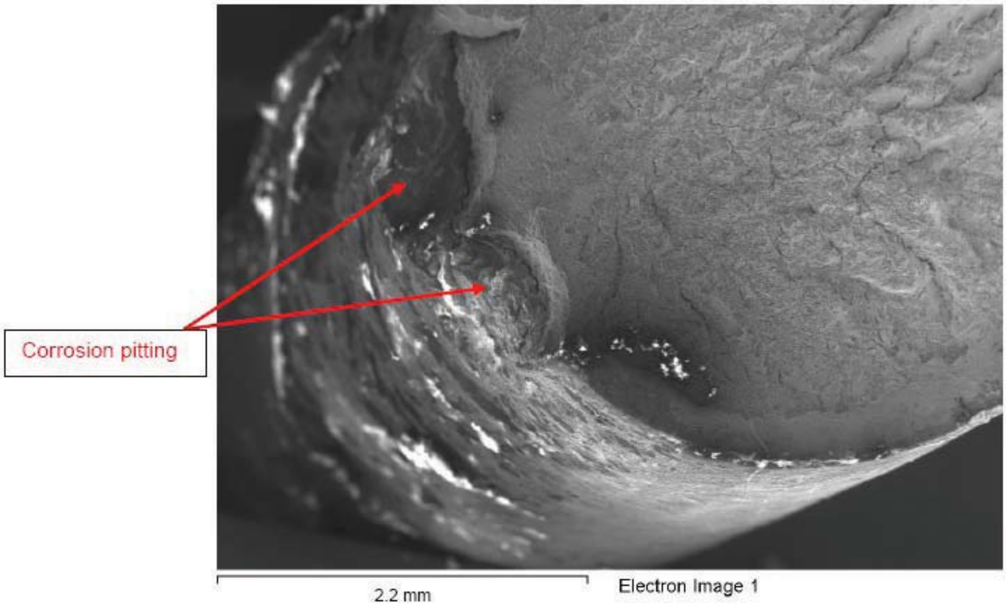

Figure II-14. Scanning electron micrograph of wire L65 fracture surface and surface with pitting

Figure II-15. Surface (top) and fracture surface (bottom) of wire W95-2

II-4.2 Scanning Electron Microscope Examination (SEM)

Evaluation of fracture surfaces with pre-existing cracks revealed that the preexisting crack surfaces were covered in corrosion products/deposits, which could not be removed by ultrasonic cleaning. It should be noted that zinc on the outer surface had essentially been depleted and that the pre-existing cracks initiated from surface pitting. Cracking then progressed transversely with little associated plastic deformation, as is characteristic of stress corrosion cracking. The preexisting crack surfaces also exhibited many longitudinal cracks.

As shown in Figure II-6, for wire specimen W94-2, fracture surface clearly exhibits three discoloration zones; two are different color oxide zones initiated during service, while the third zone, the final fracture, having developed during the tensile test. The wire fracture morphologies were examined on wire specimen W94-2. SEM evaluation revealed that the preexisting crack also exhibited beach marks, as is characteristic of fatigue crack growth during service, as shown in Figure II-16. However, the remaining fracture surfaces exhibits necking-down and a somewhat cup-cone profile revealing shear and tensile fracture zones.

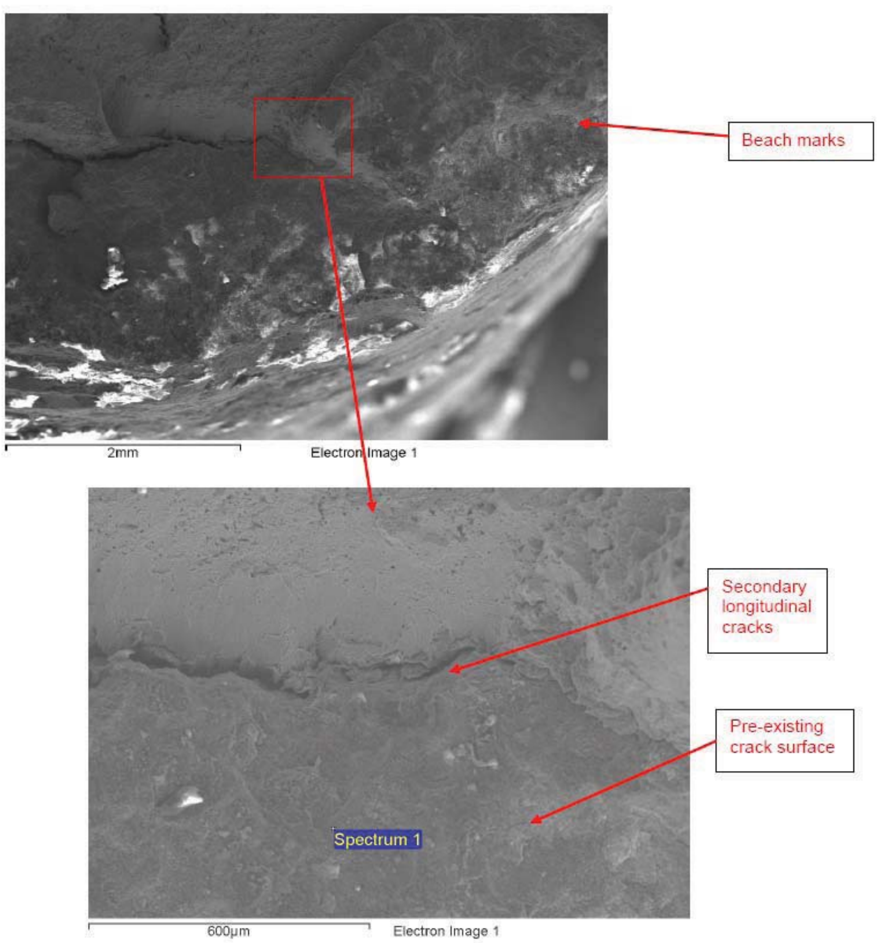

Figure II-16. Scanning electron micrograph of fracture surface
Wire W94-2 with preexisting crack

III. CABLE STRENGTH EVALUATION

In the BTC method, the cable is represented as a series of parallel wires. The wire fails when the weakest segment fails. Therefore, the wire is as strong as its weakest segment. In ASTM standard tension test, the wire demonstrates almost perfect elastic behavior until plastification occurs at a randomly located weakest section. Incremental increase in the loading usually leads to strain hardening in the weakest section, allowing for further strain increase associated with deformation concentration until ultimate strength is reached. This behavior displays elastic-plastic behavior of steel, where the specific characteristics depend on the chemistry and manufacturing process of the wire.

The stress strain curves of wire specimens tested in the lab display a linear relationship between stress and strain up to the yield point and a nonlinear behavior between the yield and the ultimate point. This behavior is described by the Ramberg-Osgood relationship as follows:

$$\varepsilon = \frac{\sigma}{E} + \alpha.\varepsilon_e \left(\frac{\sigma}{\sigma_e}\right)^n \qquad \text{(III-1)}$$

where σ, ε, E, are the stress, strain, and the Young's modulus respectively, n is the strain hardening exponent, ε_e is the yield strain, σ_e is the yield strength and α is a fitting parameter.

Test data provides measurements for yield strain, ε_e, Young's Modulus, E, ultimate strength, σ_u, and ultimate strain, ε_u .Numerous test data of deteriorated wires show a larger scatter in the ultimate strain, compared with that of the ultimate strength, where the coefficient of variation for ultimate strain is multiples of that of the ultimate strength. The coefficient of variation, for a given variable, is obtained by dividing the standard deviation by the mean. The noted significant variation in the ultimate strain provides evidence regarding the ductile versus brittle behavior of wire specimens. The BTC method uses, as input, the four variables: yield strain, ε_e, Young's Modulus, E, ultimate strength, σ_u, and ultimate strain, ε_u, where each variable is described by an appropriate probability distribution, and the cable strength is estimated separately for each investigated panel. This data is used to construct stress-strain curves for the entire set of wires in the cable cross-section by employing probabilistic techniques.

The validity of any analysis is contingent on the validity of the inputs to the analysis. In the propagation of uncertainty or variability, it is essential that any dependencies among the input variables must be considered in the analysis. Further, the statistical distributions of input variables must be properly specified, where goodness of fit test is performed for the assumed probability distributions.

In the BTC method, a correlation structure is estimated from the wire test data and proper marginal probability distribution is used for each input variable. When two variables vary together (a change in one is accompanied by a change in the other), the two variables are said to be *correlated*. For instance, Hooke's law provides a strong correlation between Young's modulus, E , and the yield strain, ε_e . Therefore assuming independence between these two variables would not be realistic. The most familiar measure of dependence between two quantities is the Pearson product-moment correlation coefficient, or "Pearson's correlation." It is obtained by dividing the covariance of the two variables by the product of their standard deviations. Appendix B provides scatter plots for the four variables; $[\varepsilon_e, E, \varepsilon_u, \sigma_u]$. A scatter plot reveals the correlation between two variables.

The next section describes the criterion for selection of the probability distributions and goodness of fit test.

III-1. Choice of Probability Distributions

According to the Engineering Statistics Handbook [8], life distribution models are chosen for one or more of the following three reasons:

- There is a physical/statistical argument that theoretically matches a failure mechanism to a life distribution model.
- A particular model has previously been used successfully for the same or a similar failure mechanism.
- A convenient model provides a good empirical fit to all the failure data.

Whatever method is used to choose a model, the model should "make sense". Distribution models such as the lognormal and the Weibull are so flexible that it is not uncommon for both to fit a small set of failure data. In the current investigation, use is made of the lognormal and Weibull distributions to model the inputs, $[\varepsilon_e, E, \varepsilon_u, \sigma_u]$. Since data for these four variables is used to infer the estimated cable strength, it is important to "test" whether the lognormal and Weibull distributions chosen are consistent with the collected data. In this investigation, either the Chi-Square (C-S), or the Kolmogorov-Smirnov (K-S) goodness of fit tests was used to decide whether a distribution model under examination is acceptable [9].

Table III-1 shows the distribution parameters for test data taken from PP 1N-2N, HSS, along the north cable. In this investigation, the ultimate strength, σ_u , and the ultimate strain, ε_u , are modeled by Weibull distribution, while the Young's modulus, E , and the yield strain, ε_e , are modeled by the lognormal distribution.

Goodness of fit test was conducted on the selected distributions for data taken from the eight investigated panels. Table III-2 shows the results of goodness of fit test performed on data taken from PP 1N-2N, along the north cable.

Table III-1 Distribution Parameters for input data at PP 1N-2N, HSS, North Cable

Data Variable	Distribution Statistics	
	Type	Parameters
σ_u (ksi)	Weibull Distribution	α = 32.068 β = 236.960
ε_u (%)	Weibull Distribution	α = 5.797 β = 4.414
E (ksi)	Lognormal Distribution	λ = 10.268 ε = 0.033
ε_e (%)	Lognormal Distribution	λ = -4.981 ε = 0.044

Goodness of fit calculations showed that the selected Weibull distribution for σ_u , ε_u , and lognormal distribution for E and ε_e present good fit to test data, see Table III-2. It is important to emphasize that these variables represent physical properties of the wire material, and therefore cannot assume negative values. Therefore the distributions selected to model these variables must have a range of [0, ∞]. Appendix B provides histograms for input and simulated distributions for PP 1N-2N, HSS.

Table III-2. Goodness of Fit Test at PP 1N-2N, HSS, North Cable

Data Variable	Sample Statistics			K-S Goodness of Fit Test	
	Mean	Std. Dev.	Coeff. of Variation	Test Statistic	Critical Value
σ_u (ksi)-Weibull	233.300	7.480	0.032	0.14203	0.18841
ε_u (%)-Weibull	4.096	0.766	0.187	0.09283	0.18841
E (ksi)-Lognormal	28799	955	0.033	0.11774	0.18841
ε_e (%)-Lognormal	0.690	0.030	0.043	0.11868	0.18841

In the following section, wire classification and the *worst-wire proportion* are determined based on the ultimate elongation of cracked wire.

III-2. Elongation Threshold Criterion, $M_{threshold}$

The ultimate elongation of wire is utilized, in the BTC method, to classify wires into two groups. Wires that fail at an ultimate elongation lower than a specific threshold elongation belong to the *worst-wire proportion*. All other wires, i.e., wires that demonstrate higher elongation than the threshold elongation are classified as the *better-wire proportion*. By the above definition, the *worst-wire proportion* contains all cracked and broken wires, as well as some intact wires, while the *better-wire proportion* contains only intact wires.

To establish a threshold elongation, $M_{threshold}$, such that we are confident that a cracked wire would fall within the *worst-wire proportion*, a one-tailed *t*-distribution at a given level of confidence, $M_{threshold}$ is used as follows:

$$M_{threshold} = \mu + t_{\alpha} . \sigma \qquad \text{(III-2)}$$

where μ and σ are, respectively, the mean and standard deviation of ultimate elongation of the set of cracked wire specimens, while t_{α} is obtained from *t*-distribution tables at a given level of confidence.

Table III-3. Ultimate Strain, for Set of Cracked Wires, ε_u

PP	**Specimen #**	**ε_u(%)**
1N-2N-HSS	62-1	3.01
89N-90N-PMS	94-2	0.7335
89N-90N-PMS	102-1	0.5117
133N-134N-PSS	117-1	0.9403
133N-134N-PSS	117-3	1.8292
133N-134N-PSS	118-1	2.8012
133N-134N-PSS	122-3	0.9517
3S-4S-HSS	8-1	0.7812
3S-4S-HSS	8-2	0.7186
3S-4S-HSS	8-3	0.6940
61S-62S-HMS	25-2	1.9984
61S-62S-HMS	25-3	0.7912
61S-62S-HMS	25-4	1.0559
90S-91S-PMS	38-3	3.3598

The ultimate elongation of the set of cracked wires is given in Table III-3. At a 99.5% level of confidence, using *t-distribution*, the threshold elongation, $M_{threshold}$ = 5.56%.

In the following section, condition of any wire is determined as broken, cracked, or intact.

III-3. Determination of Wire Condition

The possible outcome of the condition of the wire as broken, cracked or intact is treated as a discrete random variable, X , such that:

$$P\{X = x_j\} = P_j, \quad j = 0,1,2 \quad , \sum_{j=0}^{2} p_j = 1 \qquad \text{(III-3)}$$

where $x_0, x_1,$ and x_2 represent in this case broken, cracked and intact wire respectively. The probability of realizing a broken wire is p_0, while p_1 is the probability of realizing a cracked wire, and $p_2 = 1 - p_0 - p_1$ is the probability of having an intact wire. The probability of broken wires, p_0 , in each panel is determined based on the number of wires found broken during inspection. On the other hand, the probability of cracked wires, p_1, is determined from assessing the ratio of cracked samples, based on the fractographic evaluation of the fracture surfaces of all wires tested in tension, as presented in Section II-4 of this report. For determination of the probabilities of broken and cracked wires, p_0, and p_1, in the investigated panel, the effect of broken and cracked wires in the adjacent panels must be considered.

When a wire is cracked or fractured in a given panel, it redevelops its load carrying capacity after a certain length, known as the redevelopment or recovery length. While a wire that contains a crack does not lose its entire capacity to carry load, part of its load carrying capacity is lost due to the presence of the crack. The recovery length concept is applied to cracked wires, whereas a cracked wire in a given investigated panel would regain its full load carrying capacity at the end of the recovery length.

The following section introduces a discussion on the recovery length and assumptions made in this report.

III-4. Wire Recovery Length

When a cable wire under tension breaks, or cracks, at one location there is sufficient friction within the cable that at some distance from the break, or crack, the wire sustains the same tension as it were unbroken or uncracked. The frictional forces develop due to the radial pressure applied by the taut wrapping wires and cable bands. Additional pressure and friction are generated near the location of break or crack in wire due to the Poisson's effect. Because the cable is restrained from lateral expansion by the radial pressure provided by the wrapping wire and cable bands, the Poisson's effect increases the inter-wire contact forces. One can postulate a length over which all these frictional forces cumulatively equal the full tensile strength of the wire, which had broken or cracked. This length is defined as the clamp or recovery length.

Results of analysis by contact-stress theory showed that the recovery length for an 18"-Dia. cable with 7,697 parallel wires is 5-ft [10]. The conclusions of the study demonstrate the effectiveness of wrapping wire and cable bands in redeveloping the strength of a defective wire. It is important, however, to consider the effect of slippage of the wrapping wire or cable bands on the recovery length. Slippage in the cable band may occur due to loss of tension in cable band bolts. This would subsequently reduce the restored load carrying capacity of a broken or cracked wire, at the slipping band. This problem has been encountered on many suspension bridges. In 2009, failure of nine heavy-duty nuts of cable band bolts on one of the major suspension bridges in Europe has been reported. All the cable band nuts and bolts were replaced in the late 1990s as part of a project to replace the suspender ropes. An investigation into the failure of the nuts has identified a number of design and specification decisions and construction methods that may have contributed to the cracking, including replacement of the original bolts with metric versions with a thinner section than the originals. The nuts are small compared with similar ones on other suspension bridges. Another factor was the use of a higher grade of steel, which meant that the nuts are less ductile, i.e., more brittle, than the originals. Misalignment of washers may have led to uneven loading in the nuts. In addition, the protective coating was inadequate and allowed moisture to cause damage.

To account for possible slippage of unwrapped external wires and cable bands, and considering gaps of broken wires that were measured under this investigation, a broken or cracked wire is assumed to redevelop its full load carrying capacity after two consecutive panel lengths, at each end of the investigated panel. Therefore the effective number of broken or cracked wires in a panel under evaluation includes wires that are broken or cracked in the investigated panel in addition to the number of broken or cracked wires that are not developed in two flanking panels at each side of the investigated panel.

III-5. Broken Wires

The number of broken wires in the exterior ring of the cable in each panel is readily identified upon the removal of the wrapping wire prior to the wedging operations. Interior broken wires are those uncovered during the wedging operations. As explained earlier, the interior broken wires were determined in an eight-wedge pattern, in each panel.

III-5.1 Exterior Broken Wires

A total of eight (8) broken wires, along the exterior ring of the cables, were found in one panel along the north cable, PP 42N-43N, HMS. Two panels along the south cable were found to have broken wires in the exterior ring; eight (8) wires in PP 3S-4S, HSS, and one (1) broken wire in PP 136S-137S, PSS. All 17 broken wires in the exterior ring were found in the bottom segment of the cable. Wires found broken along the exterior ring of the cable are fully accessible and identified. A breakdown of broken wires is shown in Table III-4.

III-5.2 Interior Broken Wires

A total of 30 broken wires were found in the interior rings of the north cable in four panels, averaging 7.5 (≈ 8) wires per panel. Along the south cable, 17 wires were found broken in three of the four panels inspected, averaging 5.7 (≈ 6) wires per panel. It is worth noting that all the interior broken wires were uncovered in the upper portion of the cable. Figure III-1 shows an interior wire, uncovered broken in the top wedge (Wedge #1) of the cable in PP 90-91, PMS, along the south cable.

Figure III-1. Broken Wire springs out of Wedge #1, PP 90-91, PMS, South Cable

Broken wires exhibit brittle stepped fracture along fracture surfaces. The lower surface is typical of an edge crack, while the higher surface is rugged due to the final fracture of wire, see Figure III-2. It is noted that the wire cross-section has not been reduced and has failed due to the presence of an initial crack that grew in service until it reached the wire fracture capacity. The highest number of 14 interior broken wires is observed at PP 133-134, PSS, along the north cable.

The report on Mid-Hudson Bridge Contract BA 96-RE-004 noted that the "..*corrosion inhibitor placed in the earlier contracts seems to be performing its intended function. There is reasonably good coverage in the lower portions of the cable cross-section. There is limited coverage in the upper portions of the cable*". This may provide explanation to the concentration of interior wire breaks in the upper portion of the cable.

The total number of observed interior wires represents a small fraction (< 12%) of the wires in the cable cross-section. Therefore in the following analysis, the probability of broken wires, p_0, is assessed based on the observed interior broken wires, in each panel.

Figure III-2. Stepped fracture at broken end of wire, PP 90-91, PMS, South Cable

The adjacent panels were not inspected in 2009; therefore the number of interior broken wires in adjacent panels is assumed equal to the average number of interior broken wires in the inspected panels with interior broken wires. That average is 8 wires and 6 wires in adjacent panels along the north and south cables respectively. Table III-4 shows the estimated number of interior broken wires in each of the investigated eight panels.

Table III-4. Estimated Number of Interior Broken Wires in each Investigated Panel

Panel Location	**Number of Observed Broken Wires**		**Total Number of Observed Broken Wires**	**Estimated Number of Interior Broken Wires**
	Outer Ring	**Interior Wires**		
1N-2N-HSS	0	5	5	21
42N-43N-HMS	8	8	16	24
89N-90N-PMS	0	3	3	19
133N-134N-PSS	0	14	14	30
3S-4S-HSS	8	10	18	22
61S-62S-HMS	0	0	0	12
90S-91S-PMS	0	4	4	16
136S-137S-PSS	1	3	4	15

III-6. Cracked Wires

To assess the proportion of cracked wires, p_1, the number of wires that were found to contain preexisting cracks as a result of the fractographic evaluation are shown in Table III-5. The average percent cracking, along the north cable, based on the collected sample of 62 wires, is about 13%. The average cracking along south cable, based on 60 wire samples, is 5%. Because the adjacent panels were not inspected, the percent cracking in the adjacent panel is assumed equivalent to the average of 13% and 5% along north and south cables respectively.

Table III-5. Number of Cracked Wire Specimens in each Investigated Panel

Panel Location	Cracked 18-inch Wire Specimens	Cracked 72-inch Wire Specimens	Number of Cracked Wires
1N-2N-HSS	62-1	L62 & L71	2
42N-43N-HMS	0	0	0
89N-90N-PMS	94-2, 102-1	L95	3
133N-134N-PSS	117-1, 117-3, 118-1 & 122-3	L117	3
3S-4S-HSS	8-1, 8-2 & 8-3	L8	1
61S-62S-HMS	25-2, 25-3 & 25-4	0	1
90S-91S-PMS	38-3	L38	1
136S-137S-PSS	0	0	0

III-7. Strength Evaluation using the BTC Method

In the evaluation of the cable strength in each panel, per the BTC method, the input data consists of the following:

- Probability distributions for test data for intact wires, $[\varepsilon_e, E, \varepsilon_u, \sigma_u]_{Intact}$, along with developed correlation.
- Probability distributions for cracked wires, $[\varepsilon_e, E, \varepsilon_u, \sigma_u]_{Cracked}$, along with developed correlation.
- Probability of broken wires, p_0.
- Probability of cracked wires, p_1.

Using the above input data, the stress strain curve for each wire is constructed. All the wires in the cable cross-section subjected to the same strain. The strain is applied in increments, and the wire fails when it reaches its ultimate strain. Failed wires are discounted from the strength calculations. This process is repeated for the entire set of wires until all the wires reach their ultimate elongation. The load carrying capacity for the cable reaches zero at maximum elongation. The estimated cable strength is the maximum load calculated.

Table III-6 presents the results of the BTC method evaluation of the expected cable strength and expected factor of safety for the eight investigated panels.

Table III-6. Expected Cable Strengths and Safety Factors per BTC Method

Location	Number of Cracked Wires	Total Number of Broken Wires	Total Cable Force (DL+LL+T) (kips)	Expected Cable Strength (kips) (1)	Expected Factor of Safety (1)
1N-2N-HSS	2	5	10,068	30,310	3.03
42N-43N-HMS	0	16	10,716	31,542	2.94
89N-90N-PMS	3	3	10,213	29,388	2.87
133N-134N-PSS	**3**	**14**	**10,256**	**28,261**	**2.75**
3S-4S-HSS	1	18	10,082	33,292	3.30
61S-62S-HMS	1	0	10,158	33,708	3.31
90S-91S-PMS	1	4	10,233	33,674	3.29
136S-137S-PSS	0	4	10,193	34,300	3.36

(1) Cable strength and factor of safety calculations using the BTC method incorporate effect of cracking and wire breaks in two adjacent panels at each end of the investigated panel.

The next section provides forecast of the cable service life.

IV. BTC METHOD FORECAST OF CABLE LIFE

Main cable wires degrade and suffer reduction in load carrying capacity over time. The BTC method forecasts cable degradation as a function of wire mechanical properties, and time.

As explained earlier, the cable cross-section is divided into three groups, namely intact, cracked and broken wires. The broken wires group has no load carrying capacity in the investigated panel. To establish rate of degradation, we estimated the time for onset of degradation, time at which degradation is triggered, and proportions of cracked and broken wires, utilizing test data collected under this and previous investigations.

IV-1. Forecast of Degradation in Intact Wire Strength

Degradation of the strength of intact wires is estimated, based on wire test history, at different points in time, using the following model:

$$\frac{F_2}{F_1} = f(\kappa, t_1, t_2) \qquad \text{(IV-1)}$$

where F_1 and F_2 are the breaking loads corresponding to the two breaking times t_1 and t_2, and κ is a degradation kinetic that depends on environment, strength and time.

Strength data from limited specimens tested in 1986, 1987, 1989, 2003, and expected minimum of wire strength in 2009, in the controlling panel, are used to forecast the strength of intact wires.

For cracked wires, at future points in time, we need to update the proportion of cracked wires in the cable and estimate the degraded strength of cracked wires, as shown in the next section.

IV-2. Forecast of Degradation in Cracked Wire Strength

Continuous loading on the cable leads to crack growth in the cracked wires, leading to fracture when the crack depth is such that the stress intensity factor is equal to its critical value, known as the fracture toughness. Due to environmental degradation, the effective fracture toughness is reduced resulting in reduced strength of cracked wires. The environmental degradation is manifested in the appreciable reduction of the strain energy density, W_0, and fracture toughness. Therefore fracture toughness and strain energy density measurements provide important information regarding the strength degradation of cracked wires. The strength of the cracked wires at time t_2 will be assessed based on the measured fracture toughness at time t_2. The strength of the cracked wire proportion at time t_2, $(\sigma_{ult.\ cr.})_{t_2}$, is then given by:

$$(\sigma_{ult.\,cr.})_{t_2} = \frac{(K_c)_{t_2}}{Y(\frac{a}{D})\,.\,\sqrt{\pi . a_c}} \qquad \text{(IV-2)}$$

where $(K_c)_{t_2}$ is the effective fracture toughness at time t_2, a_c is the critical crack depth and $Y(\frac{a}{D})$ is the crack geometry factor.

Estimate for the fracture toughness of degraded wires was presented in section II-3 of this report. The estimate for the fracture toughness of degraded wire, at time t_2, is a function of the strain energy density, which in turn, is evaluated from the stress strain curve. A relationship between the fracture toughness and the strain energy density for a bridge wire was first introduced by BTC as follows:

$$K_c^{\,2} = \beta \,.\, W_0 \tag{IV-3}$$

where β is a function of the elastic properties of the material that is considered constant with exposure to the environmental degradation. The effective fracture toughness of degraded wire, at time t_2, $\left(K_c\right)_{t_2}$, is assessed from the following relationship:

$$\left(K_c\right)_{t_2}^2 = f\left((K_c)_{t_1}^2 \cdot \frac{(W_0)_{t_2}}{(W_0)_{t_1}} \right) \tag{IV-4}$$

where $(W_0)_{t_2}$ is the corresponding strain energy density at time t_2, while $(W_0)_{t_1}$ and $\left(K_c\right)_{t_1}$ are strain energy density and the fracture toughness of wire material at time t_1.

The following section presents forecast of cracked wire proportion in the controlling panel, PP 133-134, PSS, along north cable.

Forecast of degraded strengths for intact and cracked wires, as well as updated proportions of cracked and broken wires, at different points in time, are used to estimate the degraded cable strength.

IV-3. Forecast of Cable Strength and Safety Factor

The main cables were originally designed using working stress method with a factor of safety of 3.68, calculated at PP 133N-134N, PSS. There is no standard minimum factor of safety at which a suspension bridge must be closed to traffic. However, there appears to be consensus in the United States that traffic should not be run on a suspension bridge for any period with a factor of safety of less than 2.0. The remaining service life of the main cable is defined as the length of time until the factor of safety reaches 2.0.

At the controlling panel, PP 133N-134N, the safety factor of 2.0, based on the expected value of cable strength, is forecast in year 2041. Therefore the service life of the cable is forecast to end in year 2041. Cable augmentation measures need long lead time and should be planned well ahead of the estimated end of service life.

Determination of remaining service life of bridge cables requires consistent effort to update the condition of cables. Structural health monitoring provides an effective tool for updating ongoing degradation in bridge cables through the use of sensor technologies.

Currently, Bridge Technology Consulting (BTC) is the principal investigator for a cable mock-up experiment that furthers the understanding of internal wire degradation with the passage of time. The experiment will use an environmental chamber to mimic the degradation mechanisms that act on real bridge cables while sensor technologies track condition as the cable deteriorates. The experiment will enable the information gathered by sensors to be compared with physical damage. This will provide data for use in the BTC method for the assessment of remaining strength and service life of bridge cables. The US National Science Foundation funded the project [11].

The following section presents a summary of the previous main suspension cable investigations at the Mid-Hudson Bridge.

V. SUMMARY OF PREVIOUS INVESTIGATIONS

Several in-depth cable investigations were conducted at the Mid-Hudson Bridge in the last 25 years. In this section a brief history of the main cable studies performed to date is summarized, and a discussion is presented on the cable strengths assessed under previous investigations.

V-1. History of Main Cable Investigations at Mid-Hudson Bridge

In 1969, short lengths of each main cable were unwrapped to examine wires near mid-length of the center span, PP 74, and the south cable near the west anchorage for the first time. Two of the three plies of the wrapping wire on the cables were removed and replaced with new wire. Some deterioration of the galvanic coating and areas of steel surface corrosion and light pitting were noted on the wires.

In 1981, and 1982, wires were examined by removing one, two, or all three plies of the wrapping wire at ten locations. Areas of both cables were examined at locations in the center span and on the side spans. Increased deterioration of the wires was noted near mid-length of the center span, with lesser amounts of surface corrosion and pitting at other locations. In 1982, approximately 6.5 feet of the north cable was completely unwrapped between PP 75 and PP 76, and the wires probed or spread with wooden wedges to view the inner wires adjacent the cable perimeter. Significant corrosion and pitting were found on the outer four layers of wire at this location on the cable perimeter.

V-1.1 1986 Cable Investigation

The first in-depth cable investigation of the main suspension cables of the Mid-Hudson Bridge initiated in 1986, with an in-depth inspection of the cables. During this inspection, the wrapping wire of the main cable was removed for short lengths at selected locations. At a single location of the south cable, the wrapping wire was completely removed over a length of six feet, and the outer wires on the cable perimeter spread with wooden wedges. Five wire samples were removed from a section of the south cable examined and tested at Fritz Engineering Laboratory at Lehigh University.

V-1.2 1987 Cable Investigation

In 1987, under Phase IIA, the cable investigation continued with additional unwrapping and wedging at two locations of approximately six feet in length. Six wire samples were removed, examined and tested at Fritz Engineering Laboratory at Lehigh University.

V-1.3 1989 Cable Investigation

In 1989, Phase IIB of the investigation increased the unwrapped length of cables to between fifteen and twenty feet at three locations. At two of these locations, a suspender rope, and cable band were removed for inspection. The suspender ropes were replaced with new ropes and the original ropes were tested. Phase IIB of the 1989 investigation established procedures, needs and requirements used in Contract BA 90-012, Contract for Main Cable Investigation. Tensile tests were performed on 10 wire specimens removed from five (5) wires from north cable and three (3) wires from south cable. Ten wire specimens taken from three (3) wires from north cable and four (4) wires from south cable. Both tensile and fatigue tests were conducted at Fritz Engineering Laboratory at Lehigh University.

V-1.4 1990 Cable Investigation

The Main Cable Investigation Contract BA 90-012, Phase III, was awarded in 1990, and involved unwrapping 20% of the panels of the main cables for detailed inspection, evaluation, corrosion treatment, and rewrapping. About 10% of the total wires in the cable cross-section were exposed for examination. The Contract also included the unloading of seventeen suspender ropes and removing the cable bands at these locations for a detailed inspection of the cable under the bands. The suspender sockets were also examined at these locations. The accessible portions of all broken wires discovered were examined, removed, and retained. Metallurgical, tensile, and fatigue tests were conducted on many of the removed wire samples.

Under Contract BA 90-012, certain panels disclosed up to ten times the average number of wire breaks found in all the panels unwrapped. As a result of Contract BA 90-012, 20% of all cable panels had been examined, cleaned, treated with corrosion inhibitor, recompacted, coated with red lead paste and rewrapped and painted. This Contract was completed in 1991.

V-1.5 1991 Cable Investigation

Contract BA 91-007 was awarded in October 1991 with the objective of extending the database of cable condition, complete the cleaning, corrosion protection, and rewrapping of the cables. The scope of this Contract included unwrapping and inspection of the remaining 238 panels of a total of 298 panels of main cables to record the condition of the cables and the number of visible broken wires. During inspection, seven lines of wedges in the upper portion of each cable were driven to examine interior wires and to add corrosion inhibitor.

V-1.6 1996 Cable Investigation

Following the completion of Contract BA 91-007, it was recommended to open and inspect the cables on a five years basis. The first of these five year inspections was completed under Contract BA 96-004.

V-1.7 1998 Cable Investigation

In the second round of five year inspections, in 1998, ten panels were unwrapped and inspected with seven lines of wedges in the upper portion of each cable panel in order to examine interior wires and to add corrosion inhibitor. Wire samples were taken at four panels to investigate the presence of bacterial damage.

V-1.8 2003 Cable Investigation

In 2003/2004, Bridge Technology Consulting, BTC, was retained by New York State Bridge Authority to conduct a fracture study of the main cable wire. A total of 47 wire specimens were removed from five panels. BTC utilized the sampled wires to perform fracture toughness evaluation of the main cable wire. Enhanced tensile tests were conducted on the 47 specimens. Results of fracture toughness and tensile tests are used in this investigation in application of the BTC method.

In the following section, a discussion is provided on the assumptions made in this investigation compared with those made in previous investigations.

V-2. Degradation Assumptions and Factor of Safety in Previous Investigations

As demonstrated above, the sample used to determine the strength of cable was limited number of wires. The process used to calculate an assumed number of effective wires and estimate the factor of safety is summarized as follows:

- Deduct all exterior wires.
- Deduct the wires in the next two exterior rows in the bottom quadrant only.
- Estimate the number of interior broken wires by projecting the broken wires observed on the wedged sections.
- Estimate the remaining effective wires by deducting the exterior wires and bottom quadrant wires outlined above, plus the projected number of broken interior wires in a given panel, plus the projected number of broken interior wires in the two adjacent panels, plus one-half of the projected broken wires in the two-second adjacent panels.
- Assume that the remaining wires can be stressed to 190 ksi before a significant number of additional breaks occur, based on the long tension tests reported in the 1991 cable inspection report.

Based on the process outlined above, the lowest factor of safety, determined in 1994 Assessment of Main Cable Safety, was 2.79 for PP 120-121, PP 121-122 and PP 122-123 of the south cable. The factor of safety identified for PP 121-122 of the south cable in 1991 was reported as 3.00. In the 1991 Cable Investigation, no distinction was made between the horizontal force in the cable and the inclined tension in the cable. Had the inclined tension in PP 121-122 been used, the 1991 factor of safety would have been 2.78.

The following section presents sensitivity analysis to identify the key inputs which influence the estimated cable strength.

VI. SENSITIVITY ANALYSIS

The input values and assumptions of probabilistic models are subject to uncertainty. This section presents sensitivity analysis for the estimated cable strength due to the uncertainty in the inputs.

The purpose of sensitivity analysis is to:

(i) identify the key inputs which influence the estimated cable strength.

(ii) assess whether the estimated cable strength and the decision making process are likely to be affected by such uncertainties.

To conduct sensitivity analysis, key inputs are identified. The values for those inputs are changed above and below a specific base value for the cable strength. The effect of each input is changed at a time, while the other inputs are kept at values corresponding to the base value, and the cable strength corresponding to changed input is then assessed. This process is repeated for the different inputs, above and below the base values, and the effect of uncertainty in each input is quantified. Conclusions are then made about the ranking of sensitivity of cable strength to uncertainties in different inputs.

The following section identifies the key inputs subject to sensitivity analysis.

VI-1. Key Inputs

The following inputs are identified as influential in the evaluation of the remaining cable strength:

- Effect of adjacent panels.
- Proportion of cracked wires.
- Ultimate strength of cracked wires.
- Proportion of broken wires.

As demonstrated earlier in this report, the proportion of broken wires is estimated from field inspection observed broken wires. The proportion of cracked wires is evaluated based on the presence of preexisting cracks in tested wires. From the analysis of inspection and testing results, it is evident that both proportions demonstrate a range of variation and it is important to define the range over which the sensitivity analysis is performed. The ultimate strength of cracked wires is an input that varies depending on the effective fracture toughness at a given point in time. The effect of these inputs on the estimated cable strength is studied by varying the value of inputs as explained below.

Sensitivity analysis is performed at the controlling panel under this investigation, PP 133-134, PSS, along the north cable. The base value for this sensitivity analysis is the expected value of cable strength at PP 133-134, PSS, which is assessed based on the effect of two adjacent panels at each end, with proportion of broken wires, p_0, and proportion of wire cracking, p_1. For example, to study the effect of proportion of cracked wires, p_1, a proportion value Δ is added to p_1, while all other inputs are kept at the base value. The following inputs are used to assess the corresponding cable strength:

- Number of adjacent panels: 2 panels.
- Proportion of broken wires: p_0.
- Proportion of cracked wires: ($p_1 + \Delta$).
- Ultimate strength of cracked wires: ($\sigma_{ult.\ cr.}$).

Then, the cable strength is estimated once more, but with proportion Δ being subtracted from the proportion of cracked wires, while again the other inputs are kept at their base values, as follows:

- Number of adjacent panels: 2 panels.
- Proportion of broken wires: p_0.
- Proportion of cracked wires: ($p_1 - \Delta$).
- Ultimate strength of cracked wires: ($\sigma_{ult.\ cr.}$).

The same process is repeated for all other inputs using the same Δ, above and below the base values. The reason for choosing the same value of proportioning, Δ, is to ensure the validity of conclusions drawn regarding relative sensitivity of assessed cable strengths to uncertainties in different inputs.

The range of inputs is defined in the following section.

VI-2. Range of Sensitivity Studies

- *Effect of adjacent panels:*
  The effect of adjacent panels is not a direct input in itself, but it reflects the combined effect of proportion of broken wires and proportion of cracked wires. In the base case, we consider cracked and broken wires in two adjacent panels at each end of the investigated panel. To study the effect of adjacent panels, cable strength is evaluated for the two cases; effect of three adjacent panels, and effect of one adjacent panel at each end of the investigated panel. At PP 133-134, PSS, this corresponds to about +25% increase in proportions of broken and cracked wires in the case of three adjacent panels, and -25% in proportions of broken and cracked wires in the case of one adjacent panel. Therefore the ±25% proportion is used for the other inputs.

  Cable strength is calculated for the case of three adjacent panels at each end of the investigated panel, in which proportions of cracked and broken wires are respectively; [p_1 + 25%] and [p_0 + 25%], and for one adjacent panel at each end of the investigated panel, in which proportions of cracked and broken wires are respectively; [p_1 - 25%] and [p_0 - 25%], while all other inputs are kept at base value.

- *Proportion of cracked wires, p_1:*
  Base proportion ±25% for cracked wire proportion.

  Cable strength is calculated for both [p_1 + 25%] and [p_1 - 25%], while all other inputs are kept at base value.

- *Ultimate strength of cracked wires, ($\sigma_{ult.\ cr.}$):*
  Base proportion ±25% for ultimate strength of cracked wires.

  Cable strength is calculated for both [($\sigma_{ult.\ cr.}$) + 25%] and [($\sigma_{ult.\ cr.}$) - 25%], while all other inputs are kept at base value.

- *Proportion of broken wires, p_0:*
  Base proportion ±25% for broken wire proportion.

  Cable strength is calculated for both [p_0 + 25%] and [p_0 - 25%], while all other inputs are kept at base value.

Sensitivity analysis is performed using inputs for the controlling panel, PP 133-134, PSS, along the north cable. This panel is the most degraded panel among the eight investigated panels.

VI-3. Sensitivity Indices

A sensitivity index is defined here as a number which gives information about the relative sensitivity of the estimated cable strength to different inputs of the model. The sensitivity index (SI) is given by [12]:

$$SI = (D_{max} - D_{min}) \qquad \text{(VI-1)}$$

Where D_{max} is the output result when the input in question is set at its maximum value and D_{min} is the result for the minimum input value.

Based on calculated sensitivity index (SI) for each of the inputs, the percent change in the cable strength provides the inputs ranking shown in Table VI-1:

Table VI-1 Ranking of Inputs According to Sensitivity Index (SI)
PP 133-134, PSS, North Cable

Input	% Change in Cable Strength
Ultimate Strength of Cracked Wires	18%
Effect of Adjacent Panels	13%
Cracked Wire Proportion	10%
Broken Wire Proportion	3%

VI-4. Discussion of Results of Sensitivity Analysis

The sensitivity analysis shows the expected adverse effect on the estimated cable strength due to the reduction in the ultimate strength of cracked wires, the increase in the number of adjacent panels, and the increase in the proportions of cracked and broken wires. On the other hand, the estimated cable strength increases with the increase in the ultimate strength of cracked wires, the decrease in the number of adjacent panels, and the decrease in the proportions of cracked and broken wires. Thus the sensitivity analysis demonstrates that the output results are consistent with the direction of change in the inputs.

The sensitivity analysis concludes the following:

- The ultimate strength of cracked wires has the strongest impact on the strength of the cable. This pronounced impact is due to the high proportion of cracked wires, in PP 133N-134N, PSS, as per the fractographic evaluation.
- The effect of adjacent panels has the second strongest impact on the estimated cable strength.
- There is a strong combined impact of adjacent panels and ultimate strength of cracked wires. Therefore it is our recommendation to wedge, inspect, and sample wires from at least one adjacent panel at each end of the controlling panel, PP 133-134, PSS, along the north cable.
- The proportion of cracked wires has a large impact on the estimated cable strength. Therefore accurate assessment of cracked wire proportion is essential in the assessment of damage in degraded bridge cables. This highlights the importance of performing thorough fractographic examination of all fractured surfaces of tested wires to identify preexisting cracks, as recommended and performed by the BTC method in this investigation.
- The inclusion of fracture-based analysis is important due to the strong effect of the ultimate strength of cracked wires on the estimated cable strength.

The following section provides the observations, conclusions and recommendations of the main cable evaluation.

VII. OBSERVATIONS, CONCLUSIONS AND RECOMMENDATIONS

Under this investigation, Project C-07-11, Bridge Technology Consulting (BTC) has provided random wire sampling, wire testing, evaluation of the remaining strength, and forecast of the service life of main cables at the Mid-Hudson Bridge, using the BTC method. This section presents the observations, conclusions and recommendations of the investigation conducted by BTC.

VII-1. Observations

- The controlling average factor of safety of 2.750 is located at PP 133N-134N, PSS, along the north cable.
- The lowest average factor of safety of 3.29, along the south cable, was found at PP 90S-91S, PMS. Both controlling panels were selected, according to the BTC selection criterion based on presence of brittle fractures identified in previous investigations. Percent of corrosion had no role in identifying these two controlling panels for inspection and sampling.
- Based on the absolute minimum wire strength of 215 ksi, and 0.192-inch diameter, for a No. 6 gage wire, the minimum original cable strength is 37,828 kips for 6,080 wires. The equivalent minimum as-built factor of safety, at PP 133-134, PSS, along north cable and at PP 90-91, PMS, along south cable is 3.68. Therefore there is strength loss of 25% on the north cable and 11% strength loss on the south cable. These calculations include the effect of cracking and wire breaks in two adjacent panels at each end of the investigated panel.
- The controlling panel for cable strength, PP 133N-134N, PSS, along the north cable, displays the highest number of observed interior broken wires under this investigation.
- The BTC method does not employ corrosion stages in the assessment of cable strength. However, for comparison purposes, Tables II-5 and II-6, show the mechanical properties for each corrosion stage, per NCHRP Guidelines, in each panel.
- It is shown that there is little correlation, if any, between degradation of cable strength and visual-based evaluation of corrosion on wire surface, as defined by NCHRP Report 534 Guidelines. For seven of the eight investigated panels, per NCHRP Guidelines, the ultimate elongations for Stages 3 and 4 are higher than the ultimate elongation for Stage 2; see Tables II-5 and II-6. Further, for the eight investigated panels, per NCHRP Guidelines, the ultimate strengths for Stage 4 is higher than that for Stage 3, the ultimate strength for Stage 3, is higher than that for Stage 2, or that the ultimate strength for Stage 2, is higher than that for Stage 1; see Tables II-5 and II-6. These observations show the contradiction that results from relying on the subjective visual evaluation of corrosion stages, as defined per NCHRP Report 534 Guidelines. This illustrates the effectiveness of the BTC method not relying on visual-based stages of corrosion, which could lead to erroneous results as demonstrated above.
- As shown in the sensitivity analysis, cracking in the wires has primarily driven the degradation.

VII-2. Conclusions

The lowest calculated factor of safety of 2.75 at PP 133-134, PSS, along the north cable and 3.29 at PP 90-91, PMS, along the south cable were assessed based on two adjacent panels at each end of the panel. These factors of safety are equivalent to strength loss of 25% on the north cable and 11% strength loss on the south cable. Based on BTC degradation model, it is our forecast that the factor of safety, based on expected value of cable strength, will reach 2.0 in year 2041, at the controlling panel, PP 133-134, PSS, along the north cable. This estimates that the remaining service life of the cable is 30 years. No immediate remedial actions are required, at this time; however, the main cables have shown active degradation as evident by wire breaks and presence of preexisting cracks. Cable augmentation measures should be in place ahead of the expiration of the service life of the cable. Fractographic evaluation of all wire specimens fracture surfaces is important in the determination of preexisting cracks in tested wires.

VII-3. Recommendations

Based on the analysis of data and the resulting cable strengths and factors of safety, the following summarizes our recommendations:

- The effect of adjacent panels has a significant impact on the estimated cable strength. Therefore it is our recommendation to wedge, inspect, sample and test wires from at least one adjacent panel at each end of the controlling panel, PP 133-134, PSS, along north cable, during next cable investigation.
- Continue the current program of in-depth cable investigation on a 5-year cycle. During next cable opening in 2014, we recommend at minimum four (4) panel openings on south cable and six (6) panel openings on north cable; three of which are PP 133-134, PSS, along with its two adjacent panels.
- It is shown that there is little correlation, if any, between degradation of cable strength and visual-based evaluation of corrosion on wire surface, as defined by NCHRP Report 534 Guidelines.
- It is demonstrated in the sensitivity analysis that cracking in the wires has primarily driven strength degradation. Therefore thorough fractographic evaluation of test samples and fracture-based analysis of cracked wires are essential in upcoming cable investigations.
- Random sampling of wires eliminates bias in selecting wires for testing. Therefore BTC recommends random sampling procedures in future investigations.
- It is our recommendation to consider the required lead-time to commence cable augmentation, so the mitigating measures can be in place ahead of 2041.

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APPENDIX A REVIEW OF LITERATURE

A.1. Introduction

Bridge cable degradation manifests itself in the corrosion and reduced ultimate strength and ultimate elongation of individual wires resulting in a reduced load carrying capacity of the entire cable. The main goal of cable investigation is to assess the extent and rate of degradation and estimate the remaining strength and the safe service life of the bridge cables. Since the 1980's, different investigators provided variant approaches to the evaluation of the remaining strength of bridge cables. Two main approaches have been used; the first by Steinman for the investigation of the Williamsburg Bridge cables in 1988 and the second by Weidlinger Associates for the investigation of the Bronx-Whitestone Bridge in 1998. Other investigators without major differences have used variances of these two approaches. The approach presented by Weidlinger for the Bronx-Whitestone Bridge investigation was later developed and published in 2004 under the NCHRP Report 534, titled "Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel-Wire Cables", National Cooperative Highway Research Program.

A.2. Gumbel Distribution Strength Model

In the Steinman's investigation of the Williamsburg Bridge cables [(1)], a rating system was developed for classifying and cataloguing the degree of corrosion in the wire samples. Six (6) degrees of corrosion ranging from Grade 0 (least corrosion) to Grade 5 (worst corrosion) were defined as follows:

Grade 0: no corrosion; sample almost as in the original condition.

Grade 1: very light corrosion; majority of sample showing no corrosion but areas where some light rusting is noticeable. In general these samples still had an oil coating.

Grade 2: light corrosion; samples tend lack oiliness and the majority of the wire surface has some rusting.

Grade 3: medium corrosion; almost whole sample covered in surface rust but appears to be a uniform attack with no localized corrosion.

Grade 4: light-heavy corrosion; there is extensive discoloration and surface rusting with some localized corrosion.

Grade 5: heavy corrosion; significant decrease in wire diameter due to corrosion. Large easily removed sections of brown and orange surface rust is present with dark, black, strongly adherent rust underneath.

During the Steinman investigation program, five locations on the main cables were wedged and a total of 32 wires were removed from each location. Each wire was cut into specimens and subjected to tensile tests, which measured the tensile strength and the elongation at failure in a 10-inch-gage length. The test data was analyzed using Type-I extreme value distribution, also

(1) *Williamsburg Bridge Cable Investigation Program: Final Report*. New York State Department of Transportation & New York City Department of Transportation; Steinman, et al., New York, NY, 1988.

know as Gumbel distribution. Following the ductile wire model, the mean strengths of specimens were averaged to obtain the mean strength for the entire cable in the investigated panel. To calculate the cable strength, using the Ductile-Wire Model, the number of unbroken wires in the cable was multiplied by the mean wire strength. The same technique can be applied to determine the number of wires with an elongation of 0.6% in a 10-inch length or less after failure. To calculate the cable strength with the Brittle-Ductile Model, the broken wires and those with less than 0.6% elongation are subtracted from the original cable area, and the remaining wires are treated as ductile wires.

Several exceptions with the 1988 Steinman analysis are noted as follows:

- The use of Type-I extreme value distribution is inappropriate because it has unbounded lower support of $-\infty$. Therefore if it is properly fitted to a set of minimum values, negative values could occur for wire strength and elongation, a clearly impossible and counter-intuitive result in this context.

- The use of spatially predetermined sampling is deterministic and does not capture the random damage in the cable wire.

- The hypothesis that wires with ultimate elongation above 0.6% behave ductile is questionable. Recent cable investigations conducted by Bridge Technology Consulting revealed brittle behavior of wires with ultimate elongation well above 0.6%.

- Due to the limited body of knowledge in wire cracking up to the conclusion of the 1988 Steinman Report, no study of wire cracking; such as crack depth, orientation and fracture-based analysis of cracked wire strength were investigated. Recent work on cable strength assessment demonstrates that cracking of the high strength steel cable wire plays a significant role in the degradation of bridge wire and assessment of the ultimate strength of bridge cables as will be shown later in this project.

- The extent of cracking and embrittlement was not evaluated. This resulted in a gross evaluation of the remaining strength of the bridge cable.

- Commenting on the reduction of area of the wire, the Steinman Report states that "*As hydrogen embrittlement would, in its early stages, cause a severe reduction in this property without affecting tensile strength or elongation, this is strong evidence that hydrogen embrittlement is not seriously affecting the cable wires*." This statement contradicts the known adverse effect of hydrogen embrittlement on the bridge wire, which reduces the ultimate elongation without significant reduction in either the tensile strength or wire area.

- The Steinman Report rationale for estimating the clamping length is based on working load in the wire. This assumption is inconsistent with developing a cable failure mechanism to assess the ultimate load carrying capacity and factor of safety for the cable. Therefore it is more appropriate to use the wire strength. Employing contact-stress theory, the authors of Ref. [10] report that the recovery length for an 18-inch diameter cable with 7,697 parallel wires is 5-ft. In the late 1990s wire cuts were made on sections of a main suspension cable that were unwrapped from cable band to cable band. These wire cuts generated a significant acoustic event. The magnitude of the effects associated with a wire break is directly proportional to the amount of energy released when the wire breaks. As is known, the separation distance between the two ends of the broken wire is a means to measure the amount of energy released. In the early 2000s, wrapped wire cuts were performed at multiple locations which were locally unwrapped. As expected, the separation distance between the ends of the wire was significantly less than when the entire panel was unwrapped. This confirms that the wire wrapping plays a significant role in providing friction force on the wire and the rapid recovery of the wire tension (at least for the surface wires).

A.3. NCHRP Report 534 Guidelines

The NCHRP Report 534 relies on the visual classification of corrosion damage to the wire surface into four stages. The four stages of corrosion were first introduced by [4,5] and are defined as follows:

Stage 1: the zinc coating of wires is oxidized to form zinc hydroxide, known as “white rust”.
Stage 2: the wire surface is completely covered by white rust.
Stage 3: appearance of a small amount (20-30% of wire surface area) of ferrous corrosion due to broken zinc coating.
Stage 4: the wire surface is completely covered with ferrous corrosion.

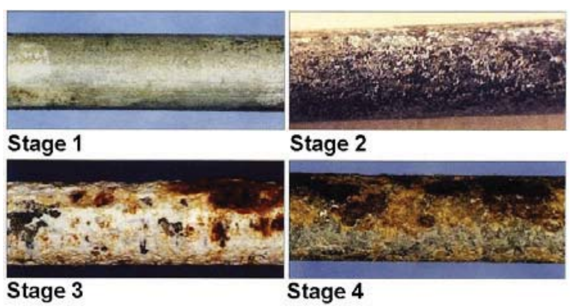


Figure A-1. The four stages of corrosion

These measures of corrosion, illustrated in Figure A-1, are visual and do not provide a quantitative assessment of the actual deterioration of the bridge wire. It should also be noted that this definition of the stages of corrosion does not describe the hydrogen embrittlement process. During inspection, only less than or about 10% of the total number of wires is accessible for visual inspection. Further, because other wires surround each wire in the cable, the inspector sees only limited part of the wire circumference, while the above definition speaks to the surface area of the wire. The corrosion stage of an observed wire in a given wedge is assigned to all the wires represented by that observed wire in the given sector. The rest of the wires are not inspected because they are not accessible for inspection; yet they are assigned the same corrosion grade as the observed wire. This results in the idealized shape of the cable cross-section, Figure A-2.

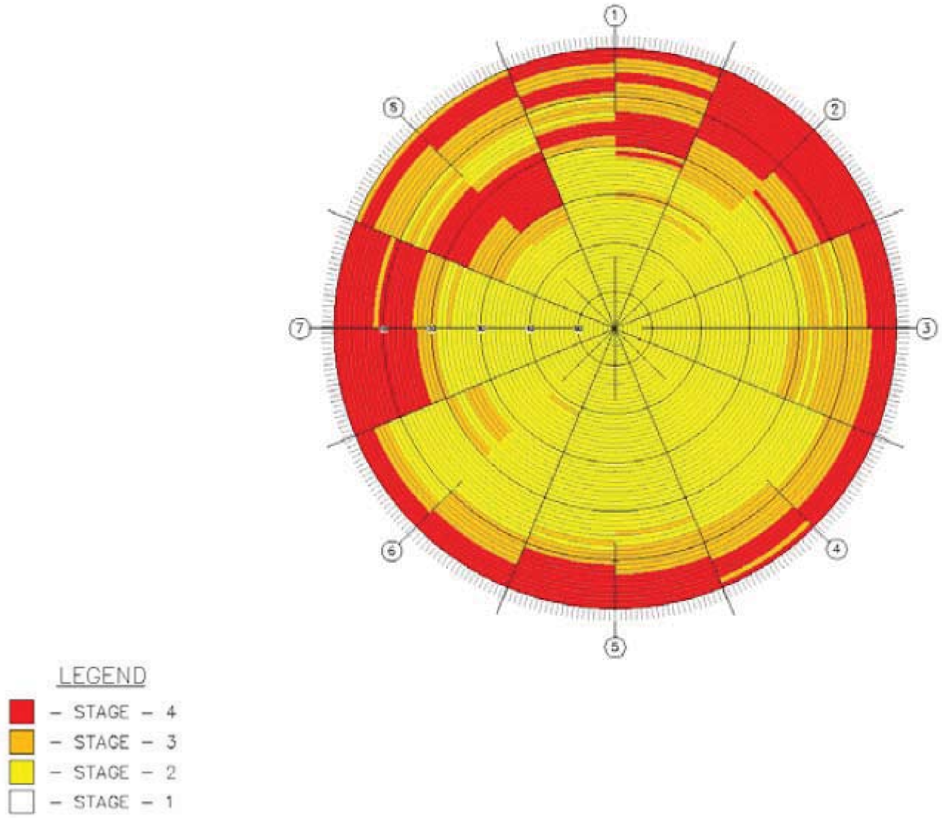
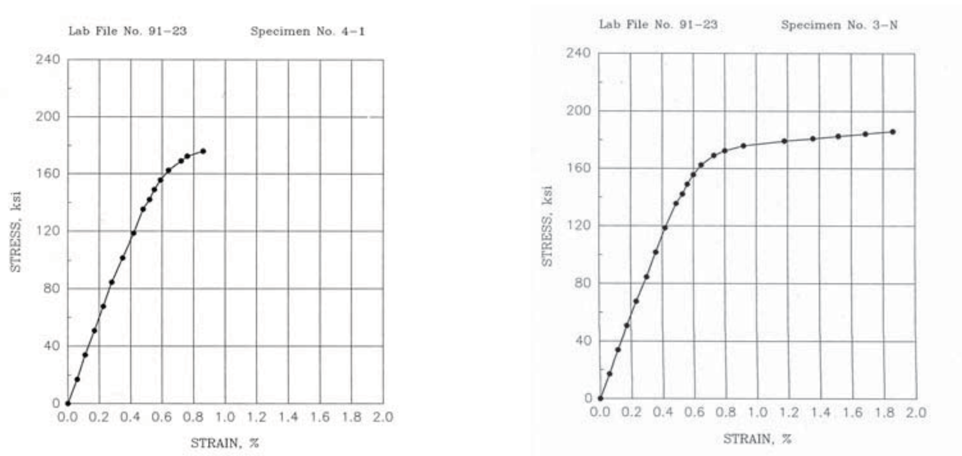


Figure A-2. Corrosion damage in a cable cross-section

During inspection, some wires from each of the corrosion stages are sampled based on the visual assessment and tested in the laboratory. The strength of each corrosion stage is assigned to the fraction of the cable cross-section identified during inspection. However, in recent investigations using the NCHRP Report, large number of wires that were visually classified as Stage 4 demonstrated higher average ultimate strength and more than double the average ultimate elongation of wires that were visually assessed as Stage 3. This is counter intuitive and could lead to inaccurate assessment of the cable strength. The significance of this is demonstrated by the two stress strain curves in Figure A-3. The wire shown in Figure A-3(a) displays half of the elongation displayed by the wire shown in Figure A-3(b), therefore the wire in Figure A-3(a) is more embrittled. It is noted that the two specimens demonstrate the same yield plateau and almost the same ultimate strength. The major and significant difference displayed by the two stress strain curves is the value of the ultimate elongation. In other words, the wire could be embrittled but its ultimate strength would not be significantly affected. This phenomenon is not measurable by the four stages of corrosion approach.



(a) (b)

Figure A-3. Stress Strain Curves for Degraded Wire

A.4. The Need for a Comprehensive Cable Strength Evaluation Method

In the two approaches, briefly outlined above, no considerations were given to random sampling of wires or fracture-based analysis of cracked wires. Random sampling accounts for the random presence of damage to the main cable wire in a given panel and along the length of the cable. Techniques that are based on spatially predetermined sampling or visual-based sampling are incapable of capturing the random damage to the cable wire. The systematic sampling is deterministic, while the visual assessment is inherently subjective and could lead to misleading results; either underestimating or more importantly overestimating the cable strength. Additionally, the presence of cracks in degrading wires emphasizes the importance of fracture-based analysis of cracked wires.

In the course of a cable investigation, it is important to evaluate cable strength utilizing modern techniques to determine the statistical error in the estimated strength. This requires the employment of random sampling techniques and fracture-based analysis of cracked wires. Modern assessment techniques employ reliability-based analysis similar to LRFD for bridge design and evaluation. In these techniques, strength and loads are defined as probabilistic quantities, from which a "*probability of failure*" is estimated. For an evaluation conducted using these criteria, the results can help establish the frequency of inspection and future cable evaluations.

The BTC method for the evaluation of the remaining cable strength provides a comprehensive modeling that utilizes state-of-the-art techniques in sampling, statistical analysis of degradation, fracture-based analysis of cracked wires and time-dependent strength degradation. The method provides sensitivity analyses that produce the different possible scenarios for the cable strength. Thus it provides the bridge owner with an effective decision making tool.

A.5. Comparison between BTC Method and NCHRP Report 534 Guidelines

In this section, a comparison is made between the BTC method and NCHRP Report 534 Guidelines, based on the following factors that influence the estimated cable strength:

- Sample size.
- Basic degradation modeling.
- Cracked wire proportion.
- Broken wire proportion.
- Effect of adjacent panels.
- Wire testing program.
- Analysis of cracked wires.
- Forecast of cable strength.

In the following, each of these factors will be examined and its ramification on the estimated cable strength and resulting factor of safety will be discussed.

A.5.1 Sample Size Determination

Wire sampling is needed to determine strength properties of wires in the cable. Sampling error refers to the fact that we use the strength properties of the sampled wires to assess the strength of the whole cable. i.e., the sampling error describes the error that results in assessing the cable strength using a sample of wires. The main objective of sample size determination is to obtain a representative group of wires so that the error in the estimated cable strength is less than or equal to an acceptable target error at high level of confidence. This section presents a comparison of sample size determination and its effect on the estimated cable strength in accordance to the BTC method and NCHRP Report 534 Guidelines.

A.5.1.1 Sample size under BTC method

To estimate an effective sample size, the BTC method assumes that the cable strength is dependent only on the ultimate strength. Data for ultimate strength, from previous investigations, is fitted to Weibull distribution, whose parameters estimators are functions of the sample size. The sample size in each panel is determined to achieve a target error, e.g. 5% at a 95% level of confidence, for the combination of cracked and intact wires sampled from each panel. Each wire in the sample size is randomly selected to provide the same probability of being selected for each wire in the available pool of wires. Therefore it is more reliable to infer the strength of the entire cable from the test results produced by randomly selected wires. While random sampling procedures do not guarantee that the sample is representative, they do increase the probability that the randomly selected wires will be representative of the cable condition. In summary, BTC sampling plan offers the following advantages:

- Captures the random nature of damage in cable wires.
- Eliminates the bias inherit in sampling based on the stages of corrosion.
- Quantifies and reduces the error in the estimated cable strength.
- Provides more reliable cable strength estimate in each investigated panel.

A.5.1.2 Sample size under NCHRP Report 534 Guidelines

NCHRP Project 10-57 and NCHRP Report 534 Guidelines determine sample size based on the presence of cracking in 13% of Stage 3 wires and 64% of Stage 4 wires. Those proportions of cracked wires were obtained for a specific "Bridge X" as per NCHRP Project 10-57. Thus, the sample size in the NCHRP Report 534 is defined and determined for each stage of corrosion.

A.5.2 Basic Degradation Modeling

The assumptions made in the degradation model have important implications on the estimated cable strength. This section delineates the basic assumptions made under this and previous investigations.

A.5.2.1 Basic degradation modeling assumptions under BTC method

In the course of a cable investigation, it is essential to evaluate cable strength utilizing objective methods that minimize the statistical error in the estimated strength. This requires the employment of random sampling techniques and fracture-based analysis of cracked wires. The BTC method relies on sampled properties of degraded wires and fracture-based analysis of cracked wires.

A.5.2.2 Basic degradation modeling assumptions under NCHRP Report 534

The main thrust in NCHRP Report 534 Guidelines is dividing the cable cross-section to the stratified stages of corrosion observed during field inspection. The corrosion stage of an observed wire in a given wedge is assigned to all the wires represented by that observed wire in the given sector. The rest of the wires are not inspected because they are not accessible for inspection. However, they are assigned the same corrosion grade as the observed wire. This procedure produces the typical corrosion map shown in Figure A-2.

A.5.3 Cracked Wire Proportion

The proportion of cracked wires has significant effect on the estimated cable strength. It is therefore crucial to have reliable determination of the proportion of cracked wires.

A.5.3.1 Cracked wire proportion under BTC method

The identification of the proportion of cracked wires in each panel, according to the BTC method, is determined based on fractographic examination of all fracture surfaces of wires tested in tension. Crack depth is measured for each of the specimens found to contain preexisting cracks. The outcome of the fractographic evaluation provides high level of confidence in the assessed proportion of cracking due to the examination of the fracture surfaces of all wire specimens.

A.5.3.2 Cracked wire proportion under NCHRP Report 534 Guidelines

The proportion of cracked wires under NCHRP Report 534 is determined as the percentage of wires defined as cracked in Stage 3 and Stage 4 wires for the entire cable. This is done irrespective of the findings of the fractographic evaluation as to the presence or absence of cracks in a given panel. Further, under NCHRP Report 534 Guidelines, effect of cracking in adjacent panels is calculated based on the percent of cracking in stages 3 and 4. Using percent of corrosion data gathered for eight (8) panels at ‘Bridge X’, Figure A-4 shows little correlation, if any, between percent cracking and percent of Stage 4 corrosion.

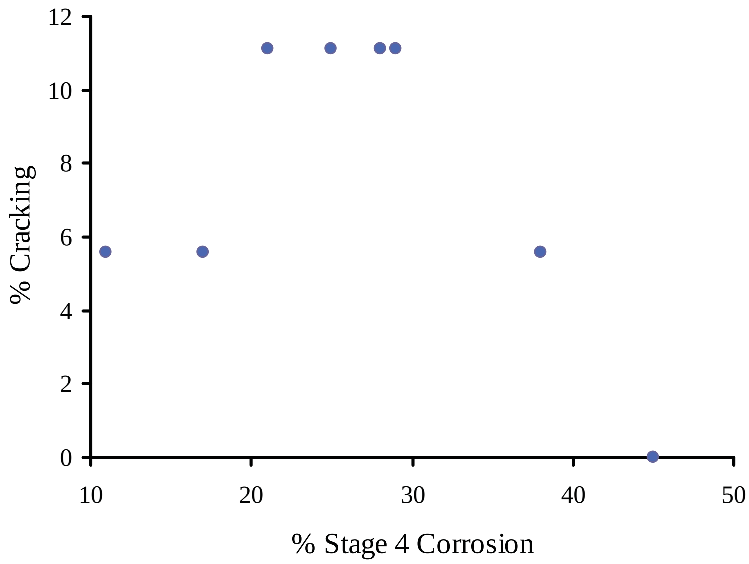


Figure A-4. Percent Stage 4 of Corrosion versus Percent Cracking in Eight (8) Panels

Bridge X is the same bridge used to develop the proportions of cracking of 64% in Stage 4 and 13% in Stage 3 in the NCHRP Report 534 Guidelines. Based on BTC fractographic evaluation of wire fractures from Bridge X, there is no evidence of the 13% cracking in Stage 3 and 64% cracking in Stage 4. The panel that contains highest proportion of Stage 4 corrosion of 45%, per NCHRP Report 534 Guidelines, revealed no cracking in the BTC fractographic evaluation. Irrespective of finding no cracks in the sample taken from this panel, the panel would possess the highest proportion of cracking. This is because per NCHRP Report 534 Guidelines, percent of cracking is determined as function of stages of corrosion as defined by NCHRP Guidelines. However, Figure A-4 shows no correlation between cracking and Stage 4 corrosion as defined by NCHRP Report 534 Guidelines.

A.5.4 Broken Wire Proportion

When a crack depth reaches a critical value, i.e., when a cracked wire reaches its ultimate strength, the wire breaks. In most bridge cables, wire breaks are observed both in the outer ring and within the interior of the cable with different degrees of severity. This section presents a comparison of broken wire analysis in the BTC method and the NCHRP Report 534 Guidelines.

A.5.4.1 Broken wire proportion under BTC method

The outer ring of the cable is fully accessible for inspection, and the number of broken wires in the outer ring is observable and identified. The probability of broken wires, p_0, in the interior rings of the cable, is assessed based on the observed broken wires, as a fraction of the total observed interior wires. Possible outcome of the condition of a wire as broken, cracked or intact is treated, in the BTC method, as a discrete random variable, X , as follows:

$$P\{X = x_j\} = P_j, \quad j = 0,1,2 \quad , \sum_{j=0}^{2} p_j = 1$$

where x_0, x_1 and x_2 represent in this case broken, cracked and intact wire respectively, p_0 is the probability of realizing a broken wire, p_1 is the probability of realizing a cracked wire, and $p_2 = 1 - p_0 - p_1$ is the probability of having an intact wire.

As such, the determination of broken wires in the BTC method is based on a probabilistic approach rather than the deterministic methods employed in the NCHRP report 534 Guidelines.

A.5.4.2 Broken wire proportion under NCHRP Report 534

Equation (4.3.3.2-1) of the NCHRP Report 534 Guidelines determine the number of broken wires in the outer ring of the cable in panel i, $n_{b1,i}$, as follows:

$$n_{bi} = \frac{n_{b1,i} . d_0}{2} \qquad (4.3.3.2\text{-}1)$$

where;
d_0 = depth into cable at which no broken wires are found
$n_{b1,i}$ = number of broken wires in the outer ring of the cable in panel i

This approach is deterministic and does not account for randomness of wire breaks.

A.5.5 Effect of Adjacent Panels

The effect of degradation in adjacent panels on the estimated cable strength in the investigated panel is incorporated by including a fraction of broken and cracked wire proportions from the adjacent panels along the redevelopment length. This section presents a comparison of the effect of adjacent panels in the BTC method and NCHRP Report 534 Guidelines.

A.5.5.1 Effect of adjacent panels under BTC method

When a wire breaks in the investigated panel, its load carrying capacity is set to zero, while a cracked wire has lower load carrying capacity than intact wires. Due to frictional forces resulting from the radial pressure applied by the taut wrapping wires and cable bands, broken and cracked wires sustain the tension load as if they were unbroken or uncracked at some distance from the break, or crack location. One can postulate a length over which all these frictional forces cumulatively equal the full tensile strength of the wire which had broken or cracked. This length has been defined earlier as the clamping or recovery length.

Based on measurements of gaps of two ends of sampled wires, the BTC method assumes that a broken or cracked wire redevelop its full load carrying capacity after two consecutive panel lengths, at each end of the investigated panel. Therefore the effective broken or cracked wires at a given evaluated panel include broken and cracked wires in the investigated panel in addition to the number of broken and cracked wires that are not developed in two adjacent panels at each side of the investigated panel.

A.5.5.2 Effect of adjacent panels under NCHRP Report 534

The effect of cracked wires in adjacent panels, in the NCHRP Report 534, is calculated as a function of the stages of corrosion

A.5.6 Wire Test Program

The wire test program determines the mechanical properties used in the analysis. Thus the reliability of the estimated cable strength as a decision making tool depends greatly on the quality of the test program.

This section provides a brief description of the significance and implications of the test program under the BTC method and NCHRP Report 534 Guidelines.

A.5.6.1 Wire test program under BTC method

As presented earlier, BTC test plan includes the following:

- Enhanced tension test.
- Tensile test on long wires.
- Fracture toughness test.
- Fractographic evaluation of fracture surfaces of all wire specimens.

A.5.6.2 Wire tests under NCHRP Report 534

Under NCHRP Report 534 Guidelines, multiple standard (18-inch) specimens are tested in tension to obtain the ultimate strength. Fractographic examination of wires is limited to a select group of wires based on visual evaluation of corrosion grade.

A.5.7 Analysis of Cracked Wires

The evaluation of the ultimate strength of cracked wire has always presented a challenge due to lack of knowledge of the fracture toughness of wire material.

A.5.7.1 Ultimate strength of cracked wires under BTC method

The presence of cracks in bridge cable wires underlines the importance of fracture-based analysis of cracked wire strength. In the traditional approach to structural design, the two major variables under consideration are the material strength and the applied stress. The structural component is assumed to be adequate if its strength is greater than the expected applied stress. Such an approach guards against brittle fracture through the introduction of a safety factor. In the presence of a crack, fracture can occur at stresses below the material's yield strength and even at the allowable design stress level. In fracture analysis, an additional variable to consider is the crack size, and the fracture toughness, K_c, replaces the material strength as the relevant material property. The fracture toughness is the parameter that characterizes the resistance of the material to brittle fracture.

A.5.7.2 Analysis of cracked wires under NCHRP Report 534

The NCHRP Report 534 Guidelines, and its accompanying NCHRP Project 10-57 Report [(2)], do not include fracture mechanics analysis of cracked wires. It is noted, however, that NCHRP Project 10-57 Report states that: "*Toughness is a parameter that can be used to determine the depth of a crack that will cause a wire to fail in service. The tensile strength of a wire has a corresponding crack depth that is derived from the theory of fracture mechanics. This property can be used to estimate the time to failure of a given wire whenever the crack depth, service loading, and the rate of crack propagation are known. Studies are being conducted to determine crack propagation rates due to electrochemical processes, but data collection requires several more years.*"

The NCHRP Report 534 Guidelines and NCHRP Project 10-57 Report do not use the fracture toughness in estimating the fracture strength of cracked wires.

A.5.8 Forecast of Cable Strength Degradation

This section provides a comparison between forecast of service life of the cable per the BTC method and NCHRP Project 10-57 Report. The NCHRP Report 534 does not include guidelines for forecasting service life of bridge cables. Guidelines for forecasting service life of the cable are given in NCHRP Project 10-57 Report.

A.5.8.1 Degradation of cable strength under BTC method

In the BTC method, wire degradation is quantified as a function of the wire measured mechanical properties. The BTC method degradation model correlates the decline of wire properties with degradation kinetics. To forecast cable strength degradation, at anytime in the future, t_2, the BTC method assesses the following:

(2) *Structural Safety Evaluation of Suspension Bridge Parallel-Wire Cables*, Prepared for National Cooperative Highway Research Program Transportation Research Board. NCHRP Project 10-57, FY 2000, Final Report, April 2004.

- Degraded strength of intact wires, $(\sigma_u)_{t2}$.
- Effective fracture toughness, $(K_c)_{t2}$.
- Degraded strength of cracked wires, $\left(\sigma_{ult.\ cr.}\right)_{t_2}$.
- Proportions of broken and cracked wires at time t_2, including effect of degradation in adjacent panels.
- Degraded strength of cable at time t_2.

The forecast for strength degradation, in the BTC method, includes the effect of proportions for broken and cracked wires in adjacent panels.

A.5.8.2 Degradation of cable strength under NCHRP Project 10-57 Report

For cables composed of bright (non zinc-coated) wires, the NCHRP Project 10-57 Report presents the following three models. These models were discussed in the Williamsburg Bridge cable investigation report referenced on page A-2 of this Appendix.

- The Minimal Maintenance Model.
- The Historic Maintenance Model.
- The Rehabilitation and Special Maintenance Model.

The Minimal Maintenance Model is based on data taken from the Williamsburg Bridge cables, which is composed of bright wires. Equation 2.6-1 of NCHRP Project 10-57 Report describes this model, as follows:

$$\Delta r = k\ t^{b} \qquad (2.6\text{-}1)$$

where;
Δr = change in wire radius
t = time in years

The constants for the Williamsburg Bridge are:

k = constant, 0.0012 inches per year
b = constant, 0.8

The remaining wire radius, $(r - \Delta r)$, at any time, t, is used to calculate the remaining area of the cable and the cable strength at time t.

The Historic Maintenance Model assumes that maintenance continues as performed in the past without change. New constants for Equation 2.6-1 are obtained by fitting the equation to measured data from previous inspections and the current one. In this model, the time is given in decades and the constants for the same bridge (Williamsburg Bridge) are:

k = 0.0045
b = 0.421

Various portions of the cable are assumed to start corroding (i.e., t = 0) at different ages. The strength at time t is arrived at using Equation 2.6-1.

The Rehabilitation and Special Maintenance Model is applied to a cable that is fully rehabilitated and carefully maintained. In this case, no degradation model is given, because "there is no reason to expect any measurable deterioration in the foreseeable future."

The NCHRP Project 10-57 Report discusses three models of strength loss rate for predicting degradation in a cable with galvanized wires:

- A linear rate of strength loss, starting at the year the bridge was completed.
- A linear rate of strength loss, starting at the first appearance of Stage 3 corrosion.
- A nonlinear rate of strength loss, increasing as the corrosion in the cable increases from stage to stage.

The first model does not account for an initial period during which no corrosion activity occurs. The nonlinear model requires experimental data to develop a graph showing the rate of deterioration of a wire in an environment similar to that inside a cable.

The second model, which does not account for an increasing rate of deterioration, has a delayed onset of strength loss, because it assumes that water does not collect inside the new cable for some period of time, followed by a period during which only Stage 1 and Stage 2 corrosion are present. The onset of Stage 3 can be estimated by assuming that the next higher stage is imminent for any observed stage in the cable. The age at onset of Stage 3 corrosion is calculated as follows, by use of Equation (2.6-2) of NCHRP Project 10-57 Report, in which the period of inactivity (t_0) is assumed 10 years:

$$t_3 = \frac{3\,(t - t_0)}{Stage + 1} + t_0 \qquad (2.6\text{-}2)$$

where;
Stage = maximum stage of corrosion observed at age t.
t = age of the bridge in years at the time of inspection.
t_0 = period during which no corrosion occurs (assumed to be 10 years).
t_3 = age of bridge in years at inception of Stage 3.

The third model is described in NCHRP Project 10-57 Report as *"under consideration in a long-term study of cable wire degradation."* The model uses data from the most recent inspection to develop a cross-section of the cable in the most seriously degraded panel. A degradation rate is calculated for each stage present in the cross-section, based on a curve showing the time required to reach that stage during a series of tests. The model requires experimental data to develop a graph showing the rate of deterioration of a wire in an environment similar to that inside a cable. The condition of the cross-section at a future date is estimated from these degradation rates.

APPENDIX B BIVARIATE SCATTER PLOTS AND INPUT VERSUS SIMULATED PROBABILITY DISTRIBUTIONS FOR A SAMPLE PANEL

B.1. Introduction

The BTC method estimates a correlation structure from the wire test data and uses proper marginal probability distribution to model each of the input variables, $[\varepsilon_e, E, \varepsilon_u, \sigma_u]$. This appendix presents bivariate scatter plots and input versus simulated probability distributions for a sample panel, PP 1-2, along north cable.

B.2. Bivariate Scatter Plots

When two variables vary together (a change in one is accompanied by a change in the other), the two variables are said to be *correlated*. A scatter plot reveals relationships or association between two variables. It can suggest various kinds of correlations between variables as shown in Figures B-1 through B-6. For instance, Hooke's law provides a strong negative correlation, as shown in Figure B-1, between yield strain, ε_e, and Young's Modulus, E. Figure B-2 shows non-structured appearance of the scatter plot which indicates no correlation between the two variables; yield strain, ε_e, and ultimate strain, ε_u.

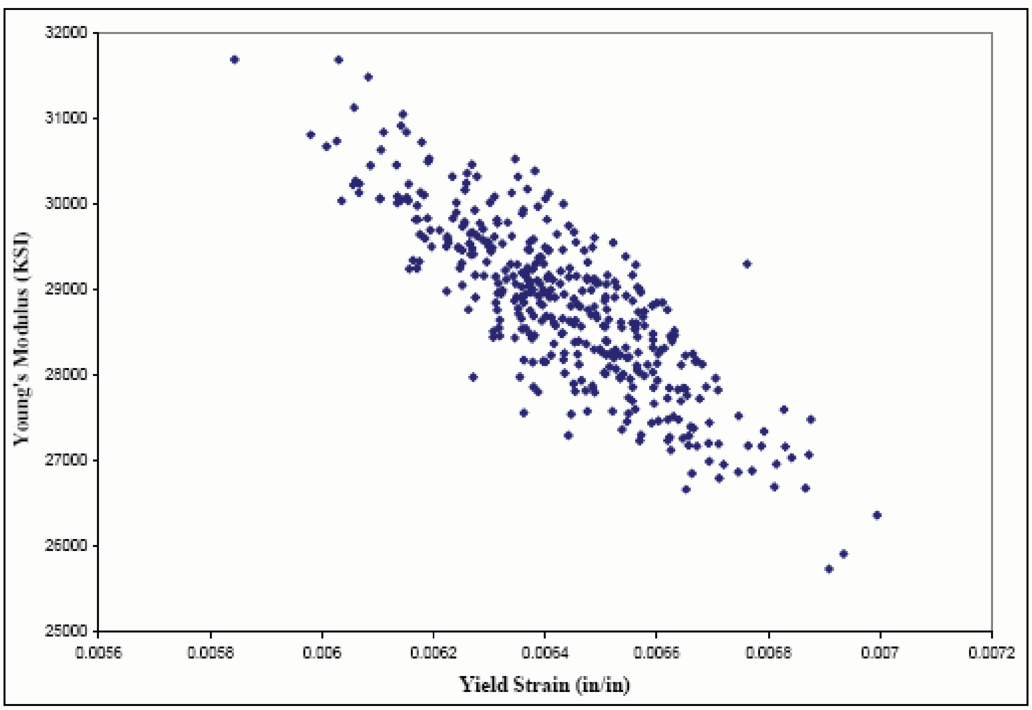


Figure B-1 Scatter Plot for Yield Strain versus Young's Modulus

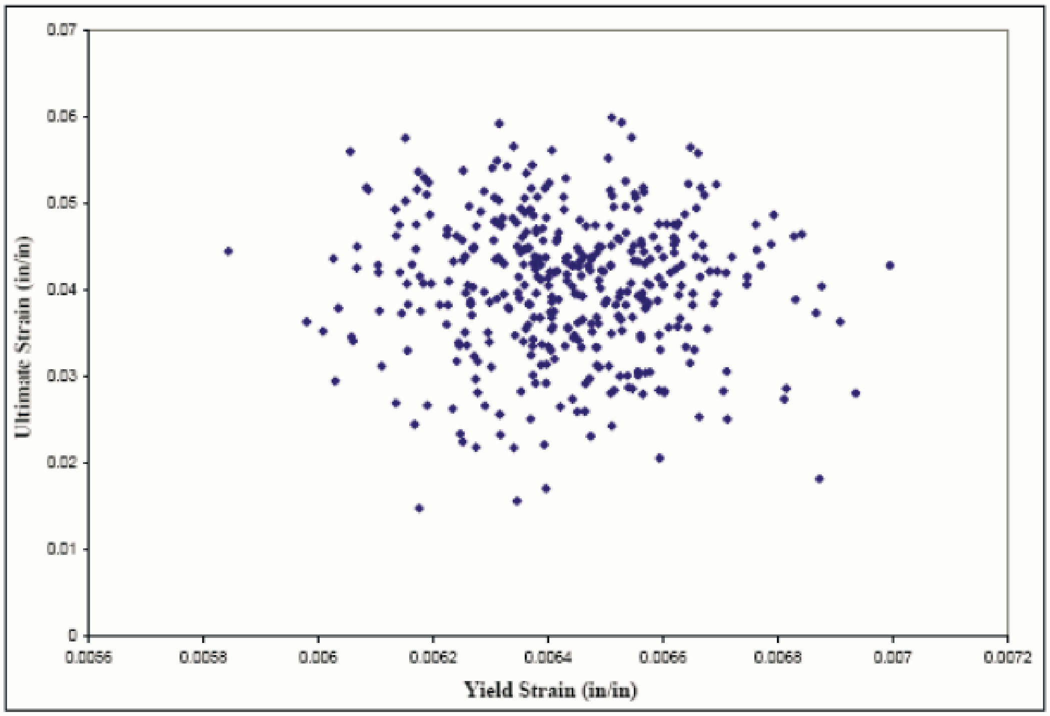


Figure B-2 Scatter Plot for Yield Strain versus Ultimate Strain

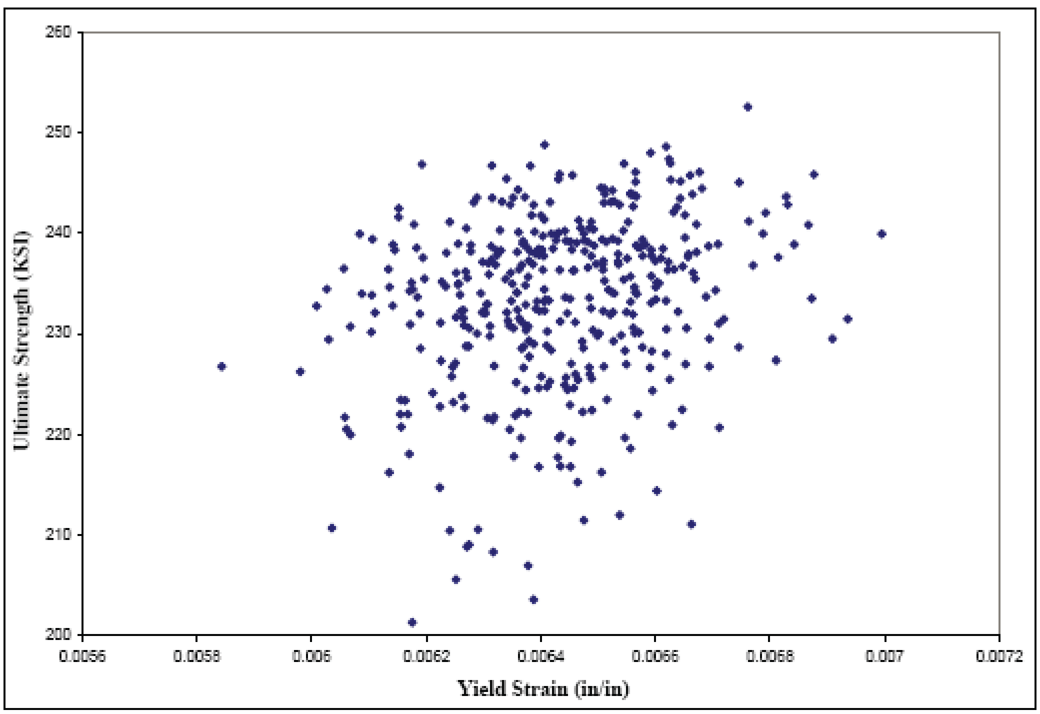


Figure B-3 Scatter Plot for Yield Strain versus Ultimate Strength

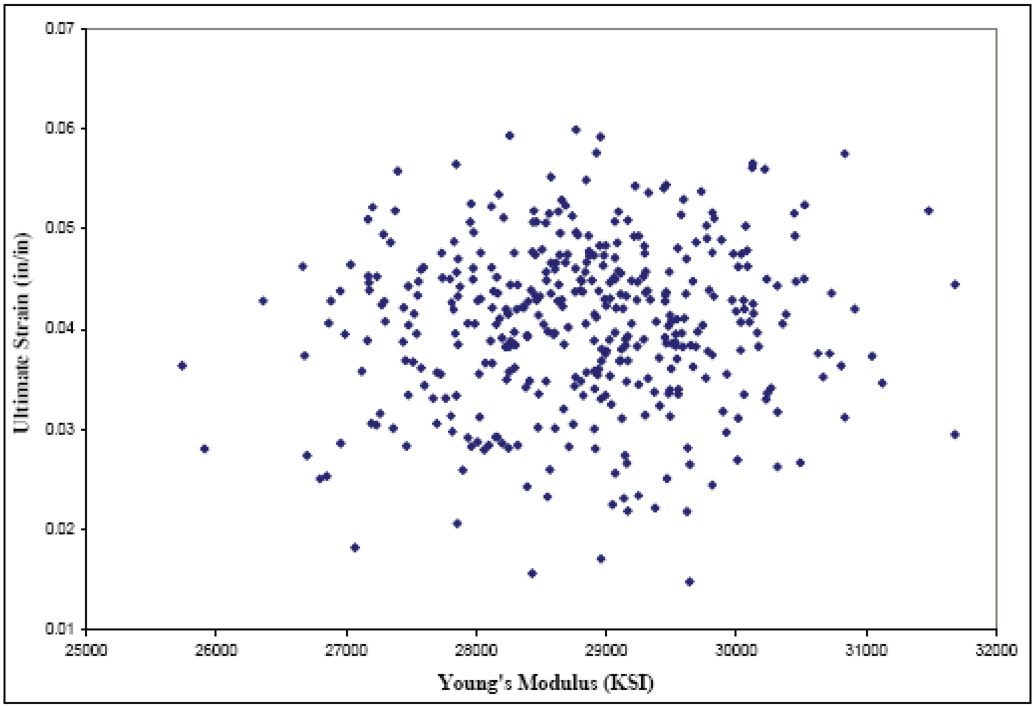


Figure B-4 Scatter Plot for Young's Modulus versus Ultimate Strain

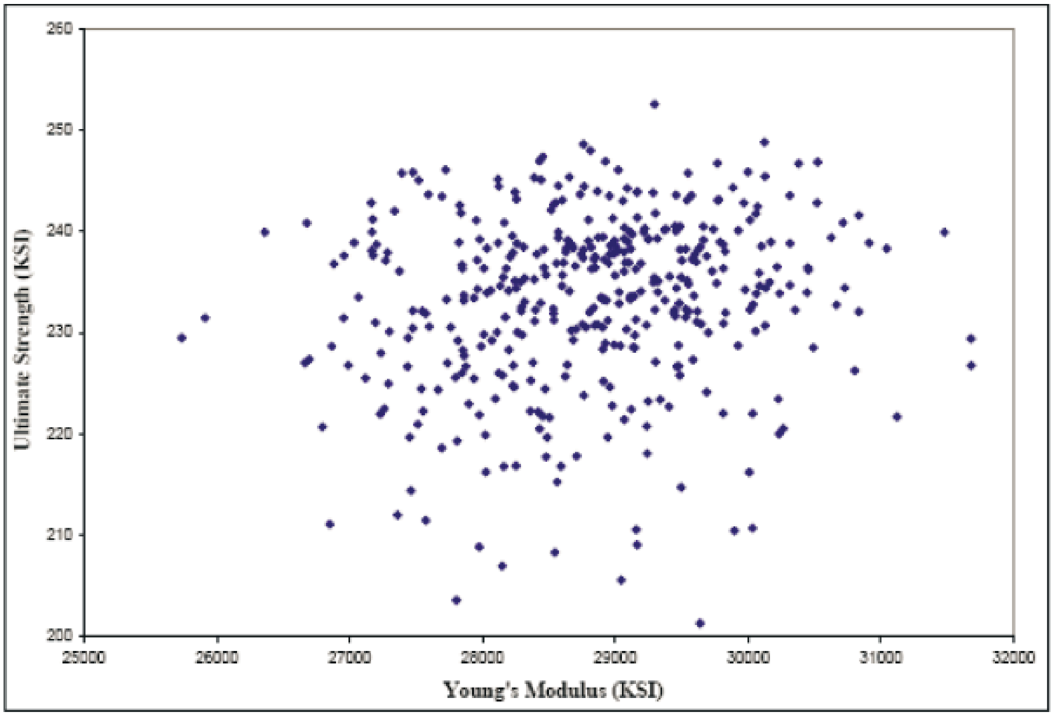


Figure B-5 Scatter Plot for Young's Modulus versus Ultimate Strength

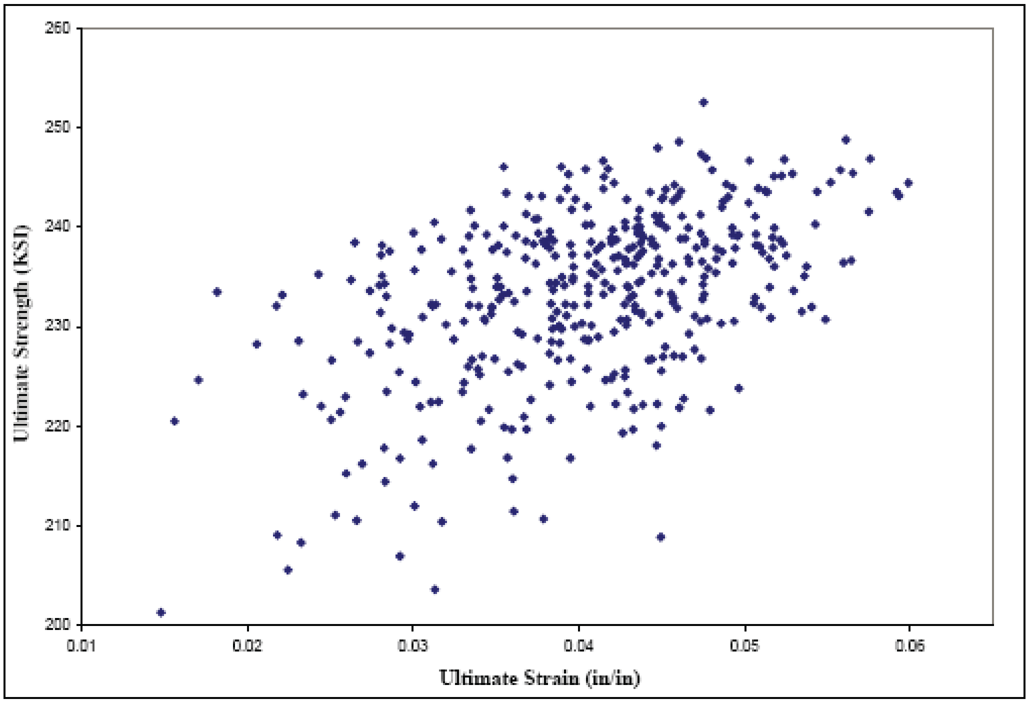


Figure B-6 Scatter Plot for Ultimate Strain versus Ultimate Strength

B.3. Input versus Simulated Probability Distributions

Goodness of fit calculations showed that Weibull distribution for ultimate strength, σ_u, and ultimate strain, ε_u, and lognormal distribution for Young's modulus, E, and yield strain, ε_e, present good fit to test data using Kolmogorov-Smirnov (K-S) goodness of fit test, see Table III-2 of this report. Figures B-7 through B-10 provide input and simulated distributions for each of the four variables.

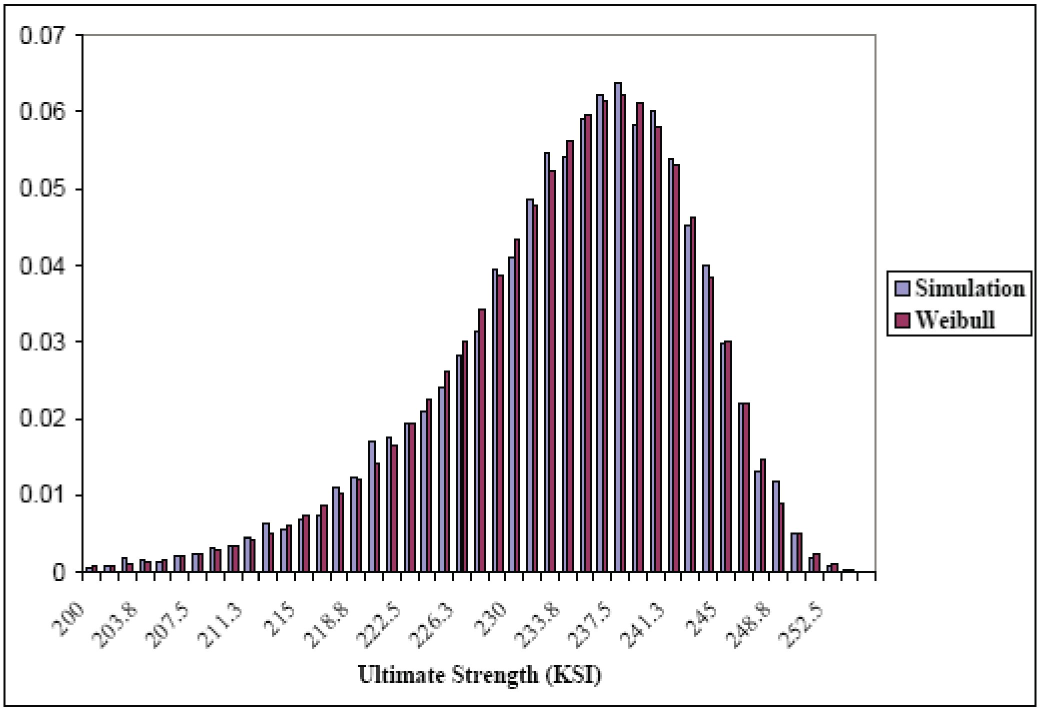


Figure B-7 Input Weibull Distribution versus Simulated Distribution for Ultimate Strength

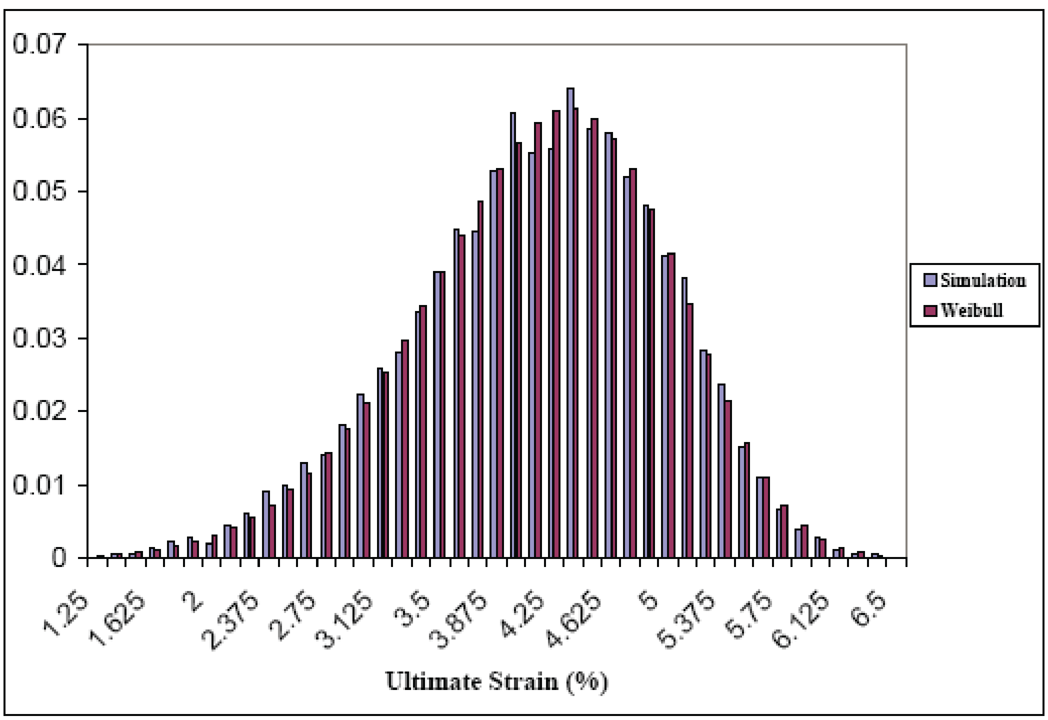


Figure B-8 Input Weibull Distribution versus Simulated Distribution for Ultimate Strain

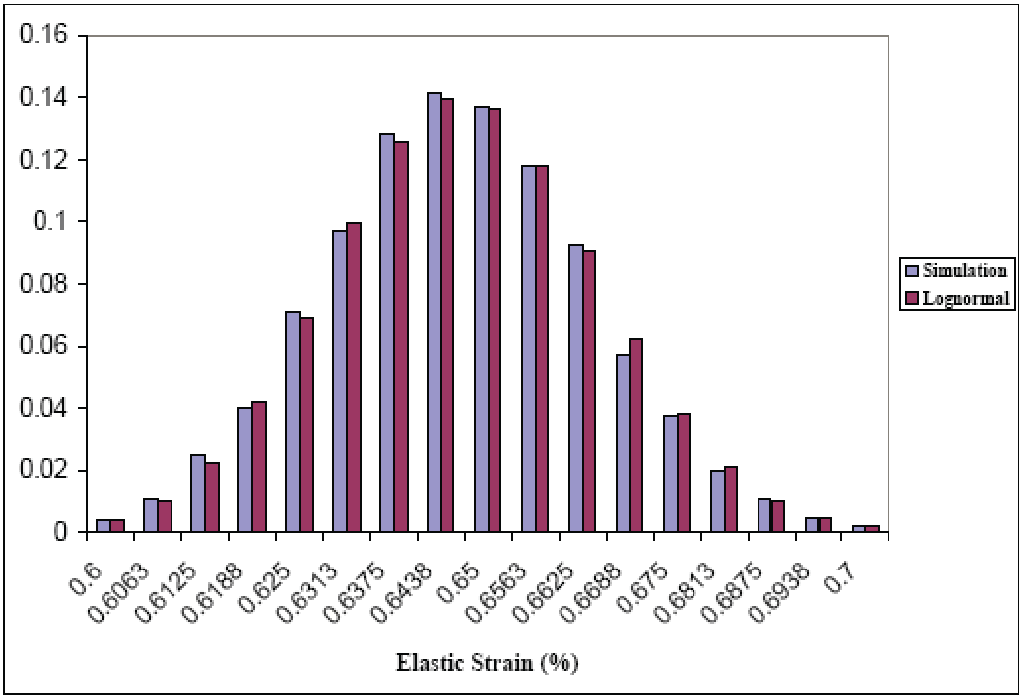


Figure B-9 Input Lognormal Distribution versus Simulated Distribution for Elastic Strain

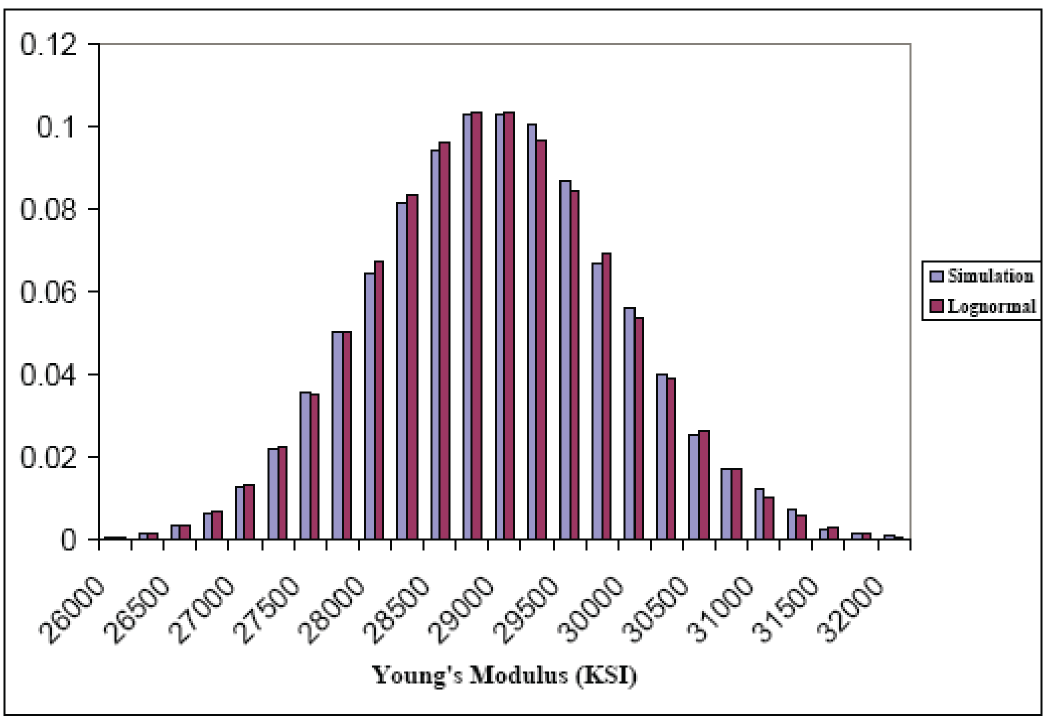


Figure B-10 Input Lognormal Distribution versus Simulated Distribution for Young's Modulus

NYSDOT Report C-07-11 presents the BTC method; a comprehensive *state-of-the-art* methodology for evaluation of remaining strength and service life of bridge cables. The BTC method is a probability-based, proprietary, patented, and peer-reviewed methodology, which applies to parallel and helical; either zinc-coated or bright wire of suspension and cable-stayed bridge cables. The BTC method includes random sampling without regard to wire appearance, mechanical testing of wires, determining the probability of broken and cracked wires, evaluating ultimate strength of cracked wires employing fracture mechanics principles and utilizing the above data to assess remaining strength in each investigated length of the cable. The probabilistic-based BTC method forecasts remaining service life of the cable by determining the rate of growth in broken and cracked wires proportions detected over a time frame, measuring the rate of change in effective fracture toughness over same time frame, and applying the rates of change to a strength degradation prediction model. The BTC method provides sensitivity analysis to identify the key inputs, which influence the estimated cable strength and assist decision-making process. The report describes the application of BTC method at Mid-Hudson Bridge in Highland, New York, conducted by Bridge Technology Consulting (BTC), under a joint contract with New York State Department of Transportation (NYSDOT) and New York State Bridge Authority (NYSBA). This project is funded in part with funds from the Federal Highway Administration (FHWA). The BTC method has been peer-reviewed by MTA Bridges & Tunnels, NYSDOT and NYSBA. To date, the BTC method has been applied to evaluate cable strength at the Bronx-Whitestone Bridge and Mid-Hudson Bridge, in the state of New York, USA.

BTC